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ALLOYS OF IRON RESEARCH, MONOGRAPH SERIES

FRANK T. SISCO, EDITOR

THE ALLOYS OF IRON AND CHROMIUM

VOL. I—LOW-CHROMIUM ALLOYS

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THE ALLOYS OF IRON AND CHROMIUM

VOL. I—LOW-CHROMIUM ALLOYS

BY

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AND

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Metallurgist, Union Carbide and Carbon Research Laboratories, Inc.

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ALLOYS OF IRON RESEARCH

MONOGRAPH SERIES

THESE monographs are a concise but comprehensive critical summary of research on iron and its alloys as reported in the technical literature of the world. They contain a discussion of all available data on binary and higher ferrous alloy systems, and on the effect of the alloying elements on carbon steel and on simple and complex alloy steels and special alloy cast irons. They provide a reliable foundation for further research and supply to the practical metallurgist, steel worker, foundryman, and engineer the essential information now scattered through more than two thousand journals and textbooks in many languages.

The authors are responsible for selection and evaluation of the data, for arrangement of subject matter, and for style of presentation. Each book, however, has been reviewed in manuscript by men especially qualified to criticize all statements. Indebtedness for this cooperation is recognized in the Acknowledgments. Finally, each manuscript has been reviewed and approved for publication by the Iron Alloys Committee.

The Committee expresses its appreciation to *The Engineering Foundation*, the *iron and steel, automotive and other industries of the United States and the American Iron and Steel Institute*, *Battelle Memorial Institute*, *The American Society for Metals*, *The American Foundrymen's Association*, and *National Bureau of Standards* for financial support, which made the laborious review of the world's literature possible; and to the libraries, engineering societies, and the technical press in the United States, Canada, England, Germany, France, Italy, Sweden, Japan, and Czechoslovakia, for cooperation in making available inaccessible reports and in permitting the use of published data.

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PREFACE

This volume is the first part of a review and summary of published information and available unpublished data on the alloys of iron and chromium. Its subject matter is restricted to a correlation of the world's knowledge of the constitution and structure of the iron-chromium alloys, the iron-chromium-carbon alloys, and the properties of those steels and cast irons containing less than 10 per cent chromium. The second part of this monograph, now in preparation, will deal with the alloys containing more than 10 per cent chromium and will include available data on that large class of materials known commonly by the terms "stainless" and "heat-resisting."

Because chromium is so widely used, not only in corrosion- and heat-resisting steels and cast irons but also in low-alloy engineering, structural, and tool steels, the preliminary review of the literature was especially laborious and time-consuming. In the preliminary search some nine thousand articles and technical papers were assembled. From this first review 478 articles and papers dealing primarily with low-chromium materials were selected for detailed study; arranged chronologically, these are appended as the bibliography for this book and are discussed in more or less detail in the text.

As is the case with a number of the widely used alloy steels and cast irons there is much recent information on plain chromium and modified chromium steels which has never been reported in the technical literature. Some of this has been incorporated in the text with the source of the data clearly indicated. Moreover, an effort has been made to differentiate between published and unpublished data for which an authority is quoted and the opinions expressed by the authors of this book. In chromium steels and cast irons patent literature plays a very large rôle. No attempt has been made in preparing this volume to review the patents or to indicate that one or another of the many analyses discussed may be covered by patents. The authors have, however, consulted the patent literature freely

and have used this information in guiding their critical review of the technical literature. Occasionally, patents have been mentioned where the specification of the patent is the only published account of some well-known process or material; but, in general, information gleaned from patents is included with more general information and the opinions expressed by the authors.

Many industrial applications have been cited under the broad interpretation that such applications are the fruits of successful research, which is in line with the belief of the authors that the reporting of such information is essential to appreciation of the underlying research work. In addition, a special chapter covering the whole field broadly has been incorporated immediately after the chapters on the equilibrium diagrams and critical points; while this chapter may not be specifically a report of research, the authors believe that it is essential to a real understanding of the data reported in the remainder of Volume I and Volume II.

As in the other monographs of the series properties are, in general, given in English units. In the chapters dealing with equilibrium diagrams only centigrade temperatures are given, in other chapters centigrade temperatures have been converted to Fahrenheit and rounded to the nearest 5 degrees. The property variously reported in the literature as elastic limit, proportional limit, or yield point has been termed yield strength in accordance with the procedure adopted in previous monographs, and discussed in Chapter I of "The Alloys of Iron and Carbon, Vol. II—Properties."

A. B. KINZEL.
WALTER CRAFTS.

New York,
July, 1937.

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Preparation of this monograph was undertaken with the knowledge that the staff of the Union Carbide and Carbon Research Laboratories, Inc. would cooperate to the fullest extent. It is a pleasure to acknowledge this help, as well as the advice given by the officers of the Laboratories, particularly Dr. F. M. Becket, President, and Mr. J. H. Critchett, Vice President. The cooperation of the members of the staff involved reviewing the literature and assembling much of the data; the authors are especially indebted to W. C. Read and E. F. Doom for their assistance in the preparation of Chapter I on the manufacture and properties of chromium and ferrochromium, W. D. Forgeng for preparing the first draft of Chapters II, III, and IV on the constitution of iron-chromium and iron-chromium-carbon alloys, John J. Egan for preparing Chapters X and XI on the low-chromium tool and special steels, C. O. Burgess for preparing Chapter XII on low-chromium cast iron, and C. E. MacQuigg for preparing Chapter XIII on steels of intermediate chromium content. The final draft for Chapters II, III, and IV on the constitution of the binary iron-chromium and the ternary iron-chromium-carbon alloys was written by J. S. Marsh, Physical Metallurgist, of the Alloys of Iron Research staff. Except for these three chapters, the authors are responsible for the selection and evaluation of the data, for the method of presentation, and for the accuracy of the conclusions.

All the members of the Iron Alloys Committee have read the manuscript of this volume; and the first or second drafts of one or more chapters have been read and criticized by many metallurgists expert in their respective fields. Their criticisms and those of the members of the Iron Alloys Committee have been given great weight, and many revisions resulted from their valued comments. However, the cooperation afforded by these collaborators, who are named below, does not necessarily indicate their complete approval of that portion of the manuscript reviewed by them.

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The economical manufacture of low-carbon, high-chromium corrosion- and heat-resisting steels is due almost wholly to the work of Dr. F. M. Becket who for 35 years has been engaged in

experimentation on the production and use of low-carbon ferrochromium. As a by-product of this work Dr. Becket has traced, from the original sources, the intensely interesting history of chromium; this history was given in an address to the Institute of Metals Division, American Institute of Mining and Metallurgical Engineers, in 1928 and printed in *Mining and Metallurgy* December 1928 and January 1929. The historical details given in the first chapter of this monograph are taken from Dr. Becket's address and should clear up with finality the confusion which has prevailed, even as late as 1935, in crediting the various discoveries which have made possible our present-day chromium steels.

A. B. KINZEL.
WALTER CRAFTS.

New York,
July, 1937.

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THE ALLOYS OF IRON AND CHROMIUM

VOLUME I

LOW-CHROMIUM ALLOYS

CHAPTER I

INTRODUCTION

History of Chromium Steels—Chromium Minerals—Preparation and Properties of Chromium Metal—Manufacture and Properties of Ferrochromium—Authors' Summary

Chromium is one of the most important alloys in modern iron and steel metallurgy. Being comparatively inexpensive, it finds a prominent position in alloy steels used for widely varying purposes. Tool and magnet steels, structural and engineering steels, armor plate and stainless steels, and high-quality cast irons are among those ferrous products found in the vast category largely dependent on chromium for their useful properties. In 1936, some 7 per cent of the manufactured iron and steel contained alloying elements in addition to those usual in carbon steels, and chromium steels represented a large proportion of this total, the chromium so used being next in total volume to manganese and silicon—elements which are added to non-alloy steels as well as to alloy steels.

It is the purpose of this monograph to summarize the facts about chromium in iron and steel including its physical and chemical effects, and its influence on the physical properties of steels containing various alloy combinations. It is further the intent to present correlated data bearing on these effects and to discuss both old and new hypotheses explaining them. It is hoped that the net result will cover the field in such a manner that the reader may have a clear understanding of the present

status of the chromium steels and cast irons, and that the research worker will have a base for further exploration. At this base he will find maps indicating the paths trodden by his predecessors with circles showing the immediate position of his fellow workers in the ever-advancing scientific and industrial front, and arrows indicating the general direction and probable character of the as yet unknown and unexplored domain immediately ahead.

A. HISTORY OF CHROMIUM STEELS

To emphasize the importance of chromium as an alloy in iron and steel is almost superfluous. While other more expensive alloys could, in many instances, be substituted for the chromium, the cost of so doing would greatly limit the entire field of application of alloy steels, and the present stainless steels would be nonexistent if chromium were lacking. It may well be said that chromium plays the same rôle in alloy steels as carbon does in plain steels. Without chromium the high-speed train, the automobile, electric heating appliances, the chemical industry, the plating industry, and the machine-tool industry would be so heavily penalized that we may well assume that they would be at a much less advanced state of development.

1. Early History of Chromium Steels.—The first practical application of chromium in iron and steel was made by Julius Baur in 1869 following his patent of 1865.* Mining tools comprised the bulk of the early product, but in 1874 the Eads Bridge over the Mississippi River was completed, the main members consisting of plain chromium steel—since then proved to contain 0.54 to 0.68 per cent chromium. Baur has been criticized because of his thought that the quality of the steel was dependent largely on chromium rather than on carbon. This is perfectly understandable as Baur was familiar with carbon steels and the improved properties which he noted as the result of the chromium addition were of sufficient magnitude so that his enthusiasm naturally led him to the thought that chromium was directly responsible. In spite of the inexactness of his views, which were, however, substantially correct as interpreted in the light of the art at the time, Baur did appreciate the benefits of chromium and his views should in no way diminish the recognition which he deserves as the first to produce chromium steels for engineering

* U. S. Patent 49,495, Aug. 22, 1865.

purposes. Interest in chromium as well as in the manufacture of ferrochromium in crucibles and blast furnaces was awakening during this period, and since 1877 there has been a continuous advance in the art of producing ferrochromium. Taking advantage of the properties conferred on steel by chromium, its use in munitions and armament was initiated by Brustlein[14] in France during the period of 1877 to 1886. He was probably the first to recognize the importance of the correlative effect of chromium and carbon. In 1892, Hadfield[19] presented his paper on chromium steels before the (British) Iron and Steel Institute and covered the field up to 16.5 per cent chromium with carbon upwards of approximately 2 per cent. It is to be noted that up to this time, and indeed for some years later, the only chromium available for steel-making additions carried with it appreciable quantities of carbon.

2. Recent Developments in Chromium Steels.—The general improvement in quality of ferrochromium, and more particularly the reduction of carbon, has been a great stimulus to the development of new chromium steels. Among the more recent developments in the structural engineering field are rolled material with 0.5 and 1 per cent chromium and steel rails with chromium up to 3 per cent. In the heat-treated steels chromium has long played an important rôle when used alone or with modifying alloys. This group of steels is of increasing interest in engineering applications involving dynamic stresses. Probably the most spectacular developments made possible by the improved ferrochromium are those in the field of stainless steel.* In 1913, Brearley developed stainless-steel cutlery with 11 to 14 per cent chromium and 0.30 to 0.40 per cent carbon; since then chromium irons with lower carbon content have found engineering application. Becket's oxidation-resistant irons and steels are the result of further increase of chromium content above 20 per cent, and the industrial development of these followed quickly. Along with these developments has come the use of high-carbon chromium steels for dies.

The now well-known low-carbon chromium-nickel austenitic steels are the ultimate result of initial investigations by Strauss and Maurer at the Krupp laboratories between 1909 and 1912.

* For an excellent detailed review of the development of these steels, the reader is referred to "The Book of Stainless Steels."[458]

Patents were granted to the Krupp works in 1912. It is significant that at the present time there is no element other than chromium available which contributes the desired corrosion and oxidation resistance to iron-base alloys, and the position of chromium in this field seems assured for some time to come.

No historical review relating to chromium, however brief, should fail to include, together with Brearley, Becket, and Strauss and Maurer, the names of A. L. Marsh, famed for his resistance wire; Ellwood Haynes, inventor of stellite; P. A. E. Armstrong and his chromium-silicon valve steels; C. M. Johnson and his work on steels resistant to cutting by the oxyacetylene flame; nor fail to credit the host of workers whose less spectacular developments and improvements have resulted in the many high-quality, decorative, structural, engineering, and tool steels available to industry today, all of which carry as an important constituent the element chromium.

B. CHROMIUM MINERALS

Chromium occurs in nature only in combination with other elements. Although a number of chromium minerals are known, the only mineral of industrial importance is chromite, a chromium-iron oxide of the composition $FeO.Cr_2O_3$ which theoretically contains 68 per cent Cr_2O_3 and 32 per cent FeO. In most of the deposits of chromite, a portion of the iron is replaced by magnesium and some of the chromium by aluminum. As a rule the ore also carries varying percentages of SiO_2. The structure of chromite is usually massive, although in many deposits it occurs as disseminated grains, frequently in a matrix of serpentine. The luster of chromite is submetallic to metallic, the density is 4.32 to 4.57 g. per cu. cm., and the hardness 5.5 on the Mohs scale.[57]

3. Chromium Ores.—Chromite is fairly widely distributed throughout the world. The important producing countries include Greece, India, Japan, New Caledonia, Rumania, Russia, Southern Rhodesia, Turkey, the Union of South Africa, and Yugoslavia. Deposits in the Philippine Islands will probably result in their inclusion in the above list before long. The ores from Turkey and Rhodesia are probably of the greatest importance for metallurgical purposes from the standpoint of the United States market. In the early years of the chromium

industry, considerable chromite was mined in the United States, but in recent years the major portion of the world's requirements has been supplied by other countries. During the World War, chromium-ore production in the United States reached interesting figures. Ridgway[474] has recently tabulated sources of chromite and discussed their probable future importance.

The most satisfactory ore for metallurgical purposes is one of massive structure, containing at least 48 per cent Cr_2O_3 and low SiO_2 and possessing a chromium-iron ratio better than 3 to 1. Where the mineral occurs as disseminated grains, concentration is necessary to obtain a product satisfactorily high in Cr_2O_3, and the small size of the resultant concentrate limits its applicability to certain metallurgical operations adaptable to the use of a fine-size raw material. Typical analyses of chromites from a number of different countries are shown in Table 1.

TABLE 1.—COMPOSITION OF CHROMIUM ORES*

Constituent	Composition, per cent				
	Rhodesian	New Caledonian	Daghardi (Turkish)	Baluchistan (Indian)	Californian (U. S. A.)
Cr_2O_3	49.62	58 28	51 67	53 54	40.92
FeO	13 96	15 10	13 58	14.50	13.89
Al_2O_3	12 72	11 17	8 52	10 68	11 00
MgO	13 08	12 58	16 04	16.26	21 00
SiO_2	7.26	0 81	5 92	2 30	10 00

* Union Carbide and Carbon Research Laboratories, Inc.

C. PREPARATION AND PROPERTIES OF CHROMIUM METAL

Chromium was probably first reduced from the ore by Vauquelin[1] in 1797 although Klaproth[2] worked in the field at the same period. Berthier in 1821[3] carried out extensive experiments in the reduction of the oxides of iron and chromium by means of carbon and prepared various alloys of chromium and iron. Even at this early date, Berthier was able to recognize the enhanced hardness, the change in magnetic qualities, and the greater resistance to acid attack as a result of the chromium addition to iron, and he prepared 1 to 1.5 per cent chromium steels from which he produced a knife and a razor of fine quality. In 1822, Stodart and Faraday[4] reported a series of now famous experi-

ments, including the production of steel to contain 1 and 3 per cent chromium. Hadfield's[323] later work on Faraday's steels indicated that the alloys containing 0.5 and 2.5 per cent chromium also contained 1 and 1.5 per cent carbon respectively. Stodart and Faraday recognized the resistance to oxidation imparted to iron alloys by chromium additions. Bunsen[5] in 1854 prepared electrolytic chromium and he too noted the acid resistance of the material. In 1856, Sainte-Claire Deville[6] prepared chromium metal following Berthier's method. In 1857, Frémy[7] told of the reduction of chromium chloride by sodium vapor and again pointed out the hardness and acid resistance. Wöhler[10] reduced chromium chloride by aluminum and by zinc and determined many of the properties of chromium as we know them today.

4. Preparation of Chromium by the Aluminothermic Process. In considering the low-carbon chromium metal of today, it is necessary to differentiate between that produced for laboratory purposes or other small-scale applications and that produced as industrial chromium metal for general metallurgical use. Pyrochemical and electrolytic methods are to be considered in the preparation of the technically pure metal.

For the preparation of industrial chromium metal two pyrochemical processes are in use: (1) aluminothermic reduction of chromic oxide (Cr_2O_3) and (2) reduction of chromic oxide by silicon. The major portion of the chromium metal manufactured in the United States today is produced by the latter process, although for some years prior to the discovery of the silicon-reduction process, considerable quantities of chromium were used which were made almost exclusively by the aluminothermic process. Chromium metal made in this way is still used to an appreciable extent.

The aluminothermic reaction is carried out in a refractory-lined container. The charge is prepared by mixing thoroughly finely ground chromic oxide and fine granular aluminum, the aluminum being supplied in proportion sufficient to combine with the oxygen contained in the chromic oxide, in accordance with the equation

$$Cr_2O_3 + 2Al = 2Cr + Al_2O_3$$

The charge may be placed in a large preheated refractory crucible and ignited by means of a small quantity of a mixture of

barium peroxide and powdered aluminum, or other mixtures capable of supplying a high local temperature. Upon ignition, a rapid self-propagating reaction takes place throughout the charge, and in a short period the entire mass becomes molten and reaches a high temperature; the chromic oxide is reduced, the metallic chromium settles to the bottom of the crucible, and the molten aluminous slag rises to the top. The reaction is sometimes accelerated by the inclusion in the charge of a small quantity of anhydrous chromic acid (CrO_3) or other equivalent accelerator, together of course with an appropriate additional quantity of aluminum to react with such accelerator.

Chromium metal prepared by the aluminothermic process contains from 97 to 99 per cent chromium and has a low content of carbon and other impurities, although it usually carries fractional percentages of aluminum.

5. Preparation of Chromium by the Silicon-reduction Process. The silicon-reduction process for the production of chromium metal is carried out in the electric-arc furnace, as the reaction between chromic oxide and silicon is not sufficiently exothermic for a self-propagating reaction. The reduction proceeds in accordance with the equation

$$2Cr_2O_3 + 3Si = 4Cr + 3SiO_2$$

With cheap power this process is considered economically preferable to the aluminothermic process, not only for the reason that metallic silicon is less expensive per unit of weight than aluminum, but also because silicon has a higher valence than aluminum, and hence somewhat less is required.

The most suitable electric furnace for use in the silicon-reduction process is one of the so-called "tilting" type, as in this style of furnace the removal of slag at frequent intervals throughout the smelting operation is greatly facilitated. The preferred shape of the furnace is cylindrical, and it may be of any size adaptable to the amount of power with which it is desired to operate. The furnace shell is generally of steel-plate construction, lined with magnesia.

The power supply may be either single- or three-phase. As this is an "open-arc" operation, a sufficiently high voltage must be available to keep the electrodes out of contact with the molten slag in the furnace, otherwise there is a tendency for the electrodes

themselves to act in the capacity of reducing agent, in which event contamination of the product with carbon cannot be avoided. The electrodes, suspended vertically, are usually of graphite and are equipped with water-cooled contacts and some mechanical device by which they may be raised or lowered at will. The power input to the furnace is controlled by this means.

The charge consists of chromic oxide and metallic silicon, both of which are crushed and thoroughly mixed; the silicon is present in substantially the amount stoichiometrically required to react with the oxygen in the chromic oxide. As one principal product of the reaction is silica, it is customary to add calcined lime to the charge to combine with the silica and form a less corrosive calcium silicate slag. Other fluxes may also be added as dictated by the furnace operation.

Smelting is conducted by charging the mixture into the furnace at a uniform rate until a batch of the desired size has been furnaced. The slag is tapped intermittently, and the metal and remaining slag are solidified at the end of each smelting batch. When the metal has been freed from adhering slag, it is crushed and sorted, sampled, analyzed, and packed.

6. Preparation of High-carbon Chromium Metal.—For special uses, a pure grade of high-carbon chromium metal is desirable as a means of adding both chromium and carbon to certain alloys. In brief, this product, which, as a matter of fact, is a chromium carbide or a mixture of chromium carbides, is made in an electric-arc furnace of a type similar to that employed in the silicon-reduction process. In this instance, however, a technically pure grade of carbon is employed as reducing agent for the chromic oxide, and the carbon is supplied in adequate excess to insure practically complete saturation of the metal with carbon. Unlike the silicon-reduction process, this reaction liberates carbon monoxide gas in accordance with the equation

$$Cr_2O_3 + 3C = 2Cr + 3CO$$

For this reason only sufficient lime plus silica slag-making constituents are added to cover the surface of the metal and prevent arcing to the metal.

Table 2 gives typical analyses of chromium metal.

7. Preparation of High-purity Chromium.—Attempts by various investigators to prepare pure chromium have usually

paralleled similar efforts to prepare many of the other pure metals on a laboratory scale. Such methods include the reduction of the chlorides or oxides with metallic reducing agents of the alkaline and alkaline-earth groups. However, in the case of chromium such trials have not led to very satisfactory results, although there are one or two notable exceptions such as the reduction of pure chromium trioxide by calcium as described by Marden and associates.* Marden and Rich† described means by which chromium powder prepared in the above manner may be compressed, sintered, swaged, and drawn to wire by a method analogous to that currently employed in the manufacture of tungsten filament.

TABLE 2.—TYPICAL ANALYSES OF CHROMIUM METAL*

Element	Composition, per cent	
	Alumino-thermic process	Electric-furnace silicon reduction
Chromium	98 to 99	98 to 99
Silicon	0 3 to 0 6	0 3 to 0.8
Iron	0 3 to 0 6	0 5 to 0.9
Carbon	0 05 to 0 15	0 05 to 0.20
Aluminum	0 2 to 0 9	Trace
Sulphur	0 05 to 0 15	0 01 to 0 05

* Union Carbide and Carbon Research Laboratories, Inc.

The problem of producing pure chromium for laboratory-test purposes became greatly simplified with the invention of the electrolytic process, and today this process is almost exclusively employed for this purpose.

8. Electrolytic Processes for High-purity Chromium.—For nearly a century considerable information has appeared in the literature concerning proposed processes for the electrodeposition of chromium. As early as 1854 Bunsen[5] obtained a deposit of chromium by the electrolysis of an aqueous solution of chromous chloride. Carveth and Curry,[35] shortly after the turn of the

* J. W. Marden, T. P. Thomas, and J. E. Conley, U. S. Patent 1,704,257, Mar. 5, 1929.

† J. W. Marden and M. N. Rich, U. S. Patent 1,760,367, May 27, 1930.

present century, experimented with the electrolysis of solutions of chromic acid, and chromates, and succeeded in obtaining some deposits of chromium from solutions of chromic acid. However, the results were erratic and no commercial use was made of the process. Some years later Sargent,[92] a coworker of Carveth, further investigated the deposition of chromium from chromic acid solutions and obtained encouraging results. Sargent's article attracted much attention, but other skilled electrochemists were unable to duplicate his results consistently. Up to 1924, all of the proposed processes had failed to give reliable results, and it was not until Fink's* work and the concurrent work of Udy† that a reliable process for chromium plating and the electrolytic production of pure chromium became available. The development of the chromium-plating process has been extraordinarily rapid since discovery of the conditions necessary for the proper control of the chromic acid solution and the other factors requisite for dependable and consistent results. There is much difference of opinion regarding the relative importance of the work of Fink and of other investigators. A perusal of the articles and patents listed by Schneidewind[207,231] together with court records† will enable those interested to draw their own conclusions.

Fink disclosed a practical, reliable, and industrially available method for the electrodeposition of chromium from chromic acid solutions. A satisfactory solution is one containing from 1 to 5 g., preferably 2.5 g., of sulphate (SO_4) radical, or an equivalent amount of other radicals, per liter of solution containing 250 g. of chromic acid. The solution must be kept adjusted to within these specified limits for continuous operation. Fink's recommended temperature of the plating bath is from 15 to 40°C. (60 to 105°F.), and for this range of temperatures the current density may vary from 36 to 144 amp. per sq. ft. of cathode surface. For decorative plating it is usual to operate at the upper end of these ranges.

Usually an insoluble anode, preferably lead, is employed. In chromium plating the cathode is, of course, the article to be coated. In the production of pure chromium the cathode may be made of any suitable metal from which the deposit of chromium

* C. G. Fink, U. S. Patent 1,581,188, Apr. 20, 1926.

† U. S. Court of Appeals, 2d Circuit, Opinion 85*F*; (2d) 577, 1936.

may be easily stripped. Sometimes a cathode of copper is employed, in which case stripping of the chromium deposit is avoided by subjecting the chromium-plated copper cathode to the action of nitric acid for complete removal of the copper.

Under favorable conditions relatively smooth chromium deposits to a maximum thickness of about $\frac{1}{8}$ in. may be built up on the cathode before the phenomenon of "treeing" starts to take place. When this occurs, the deposits become rough and uneven and, if the deposition is continued, the nodule-like "trees" eventually drop from the cathode to the bottom of the plating vat. Unlike the solutions employed in the plating of nickel, copper, silver, and a number of other metals, the "throwing power" of chromic acid solutions, even when properly controlled, is comparatively poor, and moreover the current efficiency is relatively low, usually about 10 per cent and not exceeding the order of 30 per cent.

Metallic chromium of a very high degree of purity is made today by the electrolytic process, which meets the need for certain investigations of a fundamental nature where metal of exceptional purity is imperative. By proper purification of the chromic acid and other materials entering into the process, chromium may be prepared which is substantially free from metallic impurities, but which may contain small percentages of hydrogen, oxygen, and possibly chromic oxides. Adcock[192] has shown how the oxygen may be almost completely removed from electrolytic chromium by repeated treatment in pure hydrogen at 1500 to 1600°C. (2730 to 2910°F.). Chromium prepared by Adcock's method[309] was free from metallic impurities and contained 0.004 per cent carbon and insoluble oxides from 0.01 to 0.03 per cent. Such a degree of purity is at least equal to that of most so-called pure metals.

9. Properties of High-purity Chromium.—Cast industrial chromium is a bright, crystalline, somewhat brittle metal, whereas high-purity chromium possesses the property of ductility to a considerable degree. As mentioned earlier, Marden and Rich* prepared ductile chromium by compacting and sintering "pure" chromium powder into the form of bars which could be swaged and drawn into wire, in a manner similar to that employed in the manufacture of tungsten wire.

* See footnote, p. 9.

Chromium, as electrolytically deposited from chromic acid solutions, possesses a lustrous blue-white color, is immune to corrosion by the atmosphere, and is also extremely hard and wear resistant. It is because of these inherent properties that chromium plating has become so very popular within the past few years for decorative, wear-resistant, and corrosion-resistant applications.

Unfortunately a study of the literature relating to the physical properties of chromium reveals that values are rather uncertain. Many of the constants have been determined on samples of chromium which were not of the highest degree of purity, and the effect of differences in the nature and amounts of impurities causes wide variations in the physical properties as determined by the different investigators. At the present time, chromium of a very high degree of purity may be produced by suitable treatment of metal produced by the electrolytic process, and it is not too much to hope that more accurate determinations of the physical constants of chromium will be reported in the near future. The values given in Table 3 may be accepted as being probably the best available at present.

10. Uses of Chromium Metal.—Chromium metal is employed almost exclusively in non-ferrous alloys where the presence of any appreciable percentage of iron precludes using the less expensive ferrochromium alloys. Among the more important of such applications may be mentioned the widely used cutting-tool and hard-facing alloy stellite, the very important electric-resistance heating elements of the nickel-chromium type, alloys for resistance to oxidation and corrosion, heat-treatable chromium bronzes, and other special alloys.

Chromium plating is now widely employed because of its inherent property of resisting corrosion and tarnish. Probably the most important of these applications is the chromium plating of automobile bumpers, radiator shells, headlights, handrails, decorative hardware, and plumbing fixtures, although it is also used extensively in the plating of an almost infinite variety of other articles, such as tableware where beauty and permanency of finish are desirable. Another field of application, not so well known perhaps but nevertheless of almost equal importance, is the plating of machine and engine parts, wire-drawing and other dies, punches, printing plates and the like, where electrodeposited

chromium because of its extreme hardness and wear resistance greatly prolongs the useful life of such articles. The resistance of chromium to many types of corrosion has also made chromium plating almost indispensable in various types of chemical apparatus.

TABLE 3.—PHYSICAL PROPERTIES OF CHROMIUM*

Property	Value	Reference
Atomic number	24	
Atomic weight	52 01	
Density, at 20°C., g. per cu. cm.	7 138	
Melting point, °C	1830	
Melting point, °F	3326	
Boiling point, °C	2200	
Boiling point, °F	3992	
Mean specific heat (between 0 and 100°C.), cal. per g. per °C	0 12	Schübel[60]
Latent heat of fusion, cal. per g	31.75	
Latent heat of vaporization, cal. per g	1472	†
Thermal conductivity, cal. per sq. cm. per sec. (°C. per cm.) (at room temperature)	0 165	
Mean linear coefficient of expansion, per °C. (between 20 and 300°C.)	$8\ 1 \times 10^{-6}$	Hidnert[363]
Electric resistivity, microhms per cu. cm	13 1	
Magnetic susceptibility per g. at 18°C	$3\ 7 \times 10^{-6}$	Honda[48]
Compressibility per kg. per sq. cm. at 20°C	$0\ 8 \times 10^{-6}$	Disch[96]
Hardness of cast chromium, Brinell number	130	‡
Hardness of chromium plating, Brinell number	570 to 1250	§
Hardness of chromium plating, Mohs' scale	9	§
Type of crystal lattice	Body-centered cubic	
Lattice constant, side of elementary cube	2.8787 Å.	
Closest approach of atoms	2 4930 Å.	

* "Metals Handbook"[463] unless otherwise stated.
† International Critical Tables.
‡ Union Carbide and Carbon Research Laboratories, Inc.
§ United Chromium Research Laboratories.

D. MANUFACTURE AND PROPERTIES OF FERROCHROMIUM

Frémy[7] was probably the first to suggest the production of ferrochromium in the blast furnace, although Berthier's method[3] of heating mixed oxides of iron and chromium with charcoal in a crucible was employed long before this. In 1860, Percy's

laboratory produced various grades of chromium alloys in the crucible, probably all with relatively high carbon content.[11] Kern in 1875 is reported[12] to have produced 74 per cent ferrochromium in the crucible, and Brustlein in 1875 produced 84 per cent ferrochromium with 11 per cent carbon. Blast-furnace ferrochromium or, more properly, "Tasmanian pig iron" with very low percentages of chromium was produced about 1870, a maximum of 7 per cent chromium being the rule. The production of ferrochromium of higher chromium, 24 to 40 per cent, signalized the next decade. Very high blast temperature was used to melt the chromium-iron ore, and excess coke was necessary. About this time Swedish ferrochromium was made in limited quantity containing as much as 70 per cent chromium.[15] It was only in the last decade of the century that grades containing about 40 per cent chromium became regularly available, and even these contained high carbon as viewed in the light of the present-day practice. It was at the turn of the century that Goldschmidt* first produced low-carbon ferrochromium and chromium metal by the aluminothermic process, and for many years this material filled the need for low-carbon chromium and its alloys. Even today important quantities of chromium metal are manufactured by this process.

About the same time electric-furnace reduction of chromite ore was initiated. Moissan[23] in 1893 had produced an impure chromium metal and ferrochromium containing 60 per cent chromium and 6 per cent carbon. Following his work came the series of developments and improvements which have led to the present low-carbon ferrochromium. It is this development of methods of manufacturing low-carbon ferrochromium that has made possible the more recent developments and new fields of application of ferrous chromium alloys.

Major Morehead, working at Halcomb Rock, Va., in 1897 initiated the large-scale production of an electric-furnace high-carbon ferrochromium. At about the same time Goldschmidt's aluminothermic method was applied to the reduction of chromium oxide and chromite ores with resulting high-quality low-carbon chromium metal and ferrochromium. Efforts to produce low-carbon ferrochromium in the electric furnace by reduction of

* H. Goldschmidt, German Patent 96,317, Mar. 13, 1895; U. S. Patent 578,868, Mar. 16, 1897.

chromite ores by aluminum or silicon, or modifications of such practice, continued throughout subsequent years so that in 1905 ferrochromium containing less than 1 per cent carbon, and in 1909 ferrochromium containing less than 0.5 per cent carbon, were industrially produced by these methods. The carbon content was reduced to 0.20 per cent within the next few years, and with the subsequent increased use of stainless steel and corrosion-resisting irons, ferrochromium was regularly produced containing 0.10 per cent maximum carbon. Today ferrochromium with 0.06 per cent maximum carbon is a standard product.

11. Processes for the Manufacture of High-carbon Ferrochromium.—High-carbon ferrochromium as known today usually contains from 67 to 71 per cent chromium and upwards of 4 per cent carbon. Until about 1897 the world's requirements of this alloy were manufactured either in crucibles or in the blast furnace. The crucible method was costly because of heavy fuel, refractory, and labor costs and low rate of production. The blast-furnace method of manufacture met with more favor than the crucible process, but this also had the disadvantage of high fuel cost. Moreover, the product usually contained only from 30 to 40 per cent chromium and carried a relatively high ratio of carbon to chromium, by reason of the comparatively low temperature obtainable in this furnace. The carbon content of the blast-furnace product customarily ran from 6 to 12 per cent, and other impurities such as sulphur and phosphorus had a tendency to be abnormally high. Monnartz[46] claimed to have made ferrochromium of 60 per cent chromium content in the blast furnace by raising the temperature in the furnace by means of a blast of air enriched with oxygen, but obviously this was in itself an expensive procedure. These and other considerations eventually led to the manufacture of ferrochromium in the electric furnace, and the first industrial electric-furnace plant for the manufacture of this alloy in the United States (which, incidentally, is still producing) was built and put into operation in 1897 at Halcomb Rock, Va.

12. Manufacture of High-carbon Ferrochromium in the Electric Furnace.—There are a number of types of electric furnace adaptable for the manufacture of high-carbon ferrochromium, but the one most commonly employed is an open-top, submerged-arc furnace, consisting of a reinforced stationary steel

shell lined with chromite or other refractory, equipped with adjustable vertical electrodes and a taphole for removal of the metal. The power supply is ordinarily either single- or three-phase. The electrodes, which are of either circular or rectangular cross-section, are customarily made of amorphous carbon in the higher powered furnaces, although some of the smaller furnaces are equipped with electrodes of graphite.

For the best results in manufacturing high-carbon ferrochromium a chromite is selected which contains a minimum of 48 to 50 per cent chromic oxide. A high ratio of chromium to iron is desirable, and the percentage of silica should be moderately low. Almost every kind of carbonaceous reducing agent has been used, such as coal, coke, or charcoal. Charcoal is desirable because of its high purity and its superior electric characteristics, but it is costly; hence at present coke is usually employed. The various raw materials are thoroughly mixed and fed into the furnace, whose top is customarily at the level of the charging platform. Depending upon conditions, the charging may be by hand or by means of automatic feeding equipment. As considerable quantities of carbon monoxide gas are continuously given off at the top of the furnace, it is general practice occasionally to poke the mixture with iron bars to prevent local high-pressure accumulations of gas. The gas may cause severe blows and loss of both power and stock.

As the smelting operation progresses the alloy gradually collects in the bottom of the furnace and is tapped at intervals depending on the progress of the smelting and the condition of the furnace. The alloy which comes from the furnace is collected in ladles and is retapped into metal chills.

After cooling sufficiently, any adhering slag, sand, or other foreign matter is removed from the metal, after which it is broken, sized, and packed in barrels. As there are a number of grades of high-carbon ferrochromium on the market, depending upon the carbon content desired by the steel maker, the alloy is generally graded and packed in accordance with its carbon content.

13. Processes for the Manufacture of Low-carbon Ferrochromium.—Low-carbon ferrochromium usually contains from 68 to 72 per cent chromium. The alloy is marketed in several grades, depending on the carbon content. The lowest carbon grade contains a maximum of 0.06 per cent carbon. Probably

the first attempts to produce low-carbon ferrochromium were made by refining high-carbon ferrochromium with chromium ore or iron ore to remove the excess carbon. This method was tedious and uncertain; it involved considerable loss of chromium in the slag, hence it proved to be expensive and unsatisfactory. Moreover it yielded low-grade ferrochromium, that is, an alloy containing less than 65 per cent and often less than 60 per cent chromium. Nevertheless it accounted for much of the low-carbon ferrochromium made in this country at the turn of the century. With the discovery of the aluminothermic process* considerable advancement in the art of low-carbon metallurgy was made, but this process also was costly, and the product was likely to contain excessive percentages of aluminum and sometimes also of silicon. Nevertheless ferrochromium produced by the aluminothermic process was made in quantity and fulfilled a real need prior to the production of cheaper material lower in aluminum and silicon. Reduction of chromium ore with aluminum in the electric furnace was also practiced to some extent, but this method was also expensive. It was not until Becket† discovered the method whereby refractory oxides could be reduced by silicon or silicon alloys in the electric furnace that there became available a comparatively inexpensive and satisfactory process for the manufacture of low-carbon ferrochromium. Since Becket's discovery the major tonnages of the various low-carbon ferrochromium alloys have been manufactured by the silicon-reduction process in one form or another.

The present manufacture of low-carbon ferrochromium by the silicon-reduction process is essentially an open-arc electric-furnace operation, that is, one in which the electrodes are suspended above and arc onto the molten slag. The furnace proper consists of a steel shell lined with magnesia, chromite, or other refractory selected to withstand not only the high temperatures encountered but also the slagging action of the molten products of the smelting operation. Two types of furnace are used, (*a*) stationary furnaces, equipped with tapholes for removal of metal and slag, or (*b*) tilting furnaces to allow the molten products to be removed by pouring. The vertical electrodes are of graphite

* See footnote, p. 14.

† F. M. Becket, U. S. Patents 854,018, May 21, 1907, and 891,898, June 30, 1908.

and are supported by means of water-cooled clamps. The arcs and power input of the furnace are controlled by raising or lowering the electrodes either by hand or by means of automatic regulators. The electric characteristics of different furnaces vary widely, depending to a considerable extent on the size and shape of the furnace, charge composition, and other factors.

The raw materials employed in the manufacture of low-carbon ferrochromium consist principally of chromium ore, silicon, or a silicon alloy, such as ferrochromium-silicon, and fluxing agents. The reduction proceeds in accordance with the following equation:

$$FeO.Cr_2O_3 + 2Si = 2Cr + Fe + 2SiO_2$$

Lime is added in an amount sufficient to combine, at least partly, with the SiO_2 formed by the reaction. Any chromium ore of suitable grade may be employed, and the silicon is adjusted to this and other materials in the charge.

The various raw materials are crushed and mixed before charging into the furnace. As soon as the arc has been established, smelting is started by charging the mixture into the furnace and is continued until the reaction is completed and the charge wholly melted, after which both metal and slag are tapped. Inasmuch as the melting point of low-carbon ferrochromium is considerably lower than that of pure chromium, it is the usual practice to tap the ferrochromium, rather than to allow it to accumulate in the furnace. Depending upon the carbon content of the alloy, the temperature of the metal as tapped is from 1450°C. (2640°F.) upward.

When the products of a smelting batch have cooled, a mechanical separation of the metal from the slag is effected, and the ferrochromium is thoroughly cleaned, sized, graded, and packed for shipment.

14. Properties of Ferrochromium.—In view of the fact that the several varieties of ferrochromium are seldom if ever employed in the arts as such, but rather as raw materials in the manufacture of other alloys, there has not been the same incentive to determine their physical properties as there has been with the pure metals, alloy steels, and the like. Moreover, these alloys vary considerably in the quantities and nature of other elements present, and these variations would render such determinations of doubtful value at the best. However, certain of the properties of

ferrochromium of the types on the market today may be of interest.

High-carbon ferrochromium is usually of a dull, grayish-white color, possesses a fine-grained crystalline structure, is moderately brittle, and is hard enough to scratch glass easily. When casts of this alloy are broken while at a red heat, the fractured surfaces exhibit a brilliant iridescent coloring, owing undoubtedly to the formation of infinitesimal surface films of oxide and nitrides of chromium. The melting range of ferrochromium of the usual 69 to 71 per cent chromium content varies considerably for the different ranges of carbon content, the lowest melting point, approximately 1275°C. (2325°F.), occurring with a carbon content of 2.70 per cent. As the carbon is either increased or decreased from this value, the lower melting point rises slowly, being in the neighborhood of 1475°C. (2685°F.) in the usual product which contains about 5 per cent carbon. The density of high-carbon ferrochromium changes somewhat with the different percentages of carbon, silicon, and other elements present, but may be considered for average material as approximately 7.0 g. per cu. cm.

The physical appearance of low-carbon ferrochromium is not at all similar to that of the high-carbon product. This alloy usually has a bright, almost silvery color, not unlike chromium metal, and possesses a rather coarse crystalline structure. The lowest carbon grades of ferrochromium exhibit toughness, malleability, and machinability to a considerable degree. The melting point of low-carbon ferrochromium analyzing about 70 per cent chromium and 0.20 per cent carbon has been determined as 1550°C. (2825°F.) and the density as 7.3 g. per cu. cm.

A number of the physical properties of alloys of high-purity chromium and high-purity iron are available in the literature, but it is doubtful how closely these determinations would check with similar ones made on commercial ferrochromiums containing, as they always do, small amounts of other elements.

15. Grades of Ferrochromium.—Some typical analyses of various grades of ferrochromium now produced in the United States are shown in Table 4.

16. Uses of Ferrochromium.—The extensive use of ferrochromium is due to the characteristic properties that chromium bestows upon other metals with which it is alloyed. The addition

of chromium to plain carbon steels increases the hardness and resistance to shock of such steels and at the same time imparts increased tensile strength and ductility together with decreased grain size. It is frequently used in conjunction with other alloying elements in the production of alloy steels to meet many exacting engineering specifications. Chromium has the additional property of acquiring and retaining a chemically passive state, and it is also capable of imparting this property of passivity to iron and other metals when added in a sufficient proportion. This particular property explains the large use of ferrochromium in the manufacture of corrosion- and oxidation-resistant stainless irons and steels. Inasmuch as later chapters of this monograph deal in detail with the many and varied applications of chromium in the metallurgical arts, it is needless at this time to do more than mention very briefly a few of these applications.

TABLE 4.—TYPICAL ANALYSES OF VARIOUS GRADES OF FERROCHROMIUM*

Element	Composition, per cent, for grade containing maximum carbon percentage of				
	0.06	0.50	2 00	4.50	Over 7.00
Chromium	68 to 72	68 to 72	68 to 72	67 to 71	66 to 70
Carbon	0 05 to 0 06	0 2 to 0 5	1 0 to 2 0	4 0 to 4.5	7 0 to 9 0
Silicon	0 2 to 0 8	0 2 to 0 8	0 5 to 1 0	1 0 to 3 0	1.0 to 3.0
Sulphur	0 01	0.01	0 02 to 0 05	0 05 to 0.10	0 05 to 0 10
Phosphorus	0 01 to 0 03	0 01 to 0.03	0.01 to 0 03	0.01 to 0.03	0 01 to 0.03

* Union Carbide and Carbon Research Laboratories, Inc.

High-carbon ferrochromium is added to alloy steels and irons when increased hardness, resistance to oxidation at high temperatures, resistance to shock, and resistance to abrasion are desired. Among such applications may be mentioned its use in armor plate, armor-piercing projectiles, many automobile parts, balls and liners for milling machinery, crusher parts, dies, drill steels, files, grate bars, annealing boxes and heat-resisting parts, wearing parts subject to severe abrasion, crusher rolls, and in locomotive springs, wheels, and tires.

At the present time by far the major part of the low-carbon ferrochromium is used in the manufacture of corrosion-resisting steels of the plain chromium and chromium-nickel types, for

such uses as architectural trim, cooking utensils, oil-cracking stills, turbine blades, containers for milk, beer, and chemicals, automobile trim, high-strength structures, and the like. Additional applications of alloys to which low-carbon ferrochromium is added either alone or in conjunction with other alloying elements include annealing boxes, automobile steels, high-speed tool steel, magnet steel, marine parts, valve steels, electric-resistance elements, and others.

A recent development along these lines is the discovery by Franks* that the physical properties of certain chromium alloy steels may be improved by the addition of nitrogen as an alloying element. Such steels carrying nitrogen in a ratio of 1 part of nitrogen to 100 to 200 parts of chromium exhibit a refinement in grain, as well as an increase in strength, density, and toughness. High-nitrogen ferrochromium† with 0.75 per cent nitrogen and 0.15 per cent carbon maximum is now available in the United States as well as abroad.

17. Special Iron-chromium Alloys for Foundry Use.—Special chromium alloys possessing lower melting ranges and greater rates of solution in iron than regular grades of ferrochromium are marketed in this country for foundry use. Prominent among these are high-carbon high-silicon, and chromium-copper-silicon compositions of which the following are typical ranges:

Type	Composition, per cent			
	C	Cr	Si	Cu
High-carbon high-silicon	4 to 5	62 to 66	7 to 10	
Chromium-copper-silicon	1 to 1 5	58	10	6 to 7

The high-silicon ferrochromium is usually supplied as 8 mesh and finer for ladle additions, the chromium-copper-silicon in the form of briquettes for cupola additions.

For cupola additions, chromium briquettes have found increasing favor in recent years. These are prepared to contain 2 lb. of chromium in the form of high-carbon ferrochromium which in turn represents approximately 85 per cent of the total weight of the briquette. The practice permits the use of fine-size ferrochromium which is more readily melted than large lumps, and the

* R. Franks, U. S. Patents 1,990,589, 1,990,590, and 1,990,591, Feb. 12, 1935.

† W. C. Read, U. S. Patent 2,027,837, Jan. 14, 1936.

binder, Portland cement, protects the chromium from oxidation until the melting zone is reached.

18. Use of Chromium Ore and Stainless Scrap in Direct Processes.—With the beginning of production of stainless steel on a tonnage basis, there has been considerable investigation of the possibilities of preparing iron-chromium alloys with or without added constituents such as nickel, copper, molybdenum, and the like, by reducing chromium from chromium ore directly into a steel bath and thus obtaining from 12 to 30 per cent chromium in the steel without the use of a separately prepared ferroalloy. In producing the low-carbon steels it is necessary to use silicon, or its equivalent, for reducing the chromium ore, and to handle large quantities of relatively refractory slags. This operation is similar to that carried out in the production of ferrochromium, but in ferroalloy production the furnaces are designed for the prevailing temperatures and slag volumes. The steel-making furnaces used in direct-process operation are, on the contrary, necessarily designed for steel melting and refining rather than for ore reduction. Moreover, it is necessary to combine reducing and refining functions in one operation, which makes the control of uniformity of quality of the final product difficult. In spite of much large-scale experimentation with this process there is today only one producer of stainless steel in four of the major stainless-steel-producing countries—United States, England, Germany, and Sweden—who uses chromium ore rather than low-carbon ferrochromium as a source of chromium in the steel-making operation. The use of stainless-steel scrap as a partial source of chromium for stainless-steel ingots is also an important factor in the economics of the direct process, and the increased ability of the steel maker to remelt both mill and fabricating-shop stainless scrap will have a direct bearing on the future of any direct-process operations.

The so-called direct process consists essentially of preparing a steel bath of low carbon content together with a voluminous slag containing a large proportion of chromium oxide, added as chromium ore, and subsequently reducing the chromium from this slag to the bath by means of silicon, generally added as ferrosilicon. Relatively long time at high temperature is necessary to complete the reduction. This operation is so much more a steel-making problem than a ferroalloy problem that it has been

treated at greater length in the appropriate chapter of Volume II. There, consideration is also given to methods and to variations of the direct process, such as the high-carbon ferrochromium process and combinations of the ore process and the high-carbon ferrochromium process with stainless-scrap remelting, all of which depend on silicon as the major reducing agent.

E. AUTHORS' SUMMARY

1. Chromium was used as an alloying element in steels for mining tools as early as 1869, and in 1874 structural steels containing about 0.60 per cent chromium were used in bridge construction in the United States. The first application of chromium steels to munitions and armament was made in France between 1877 and 1886. The development of economical methods for the production of low-carbon ferrochromium in the first decade of the twentieth century stimulated greatly the use of chromium steels and was directly responsible for the development, after 1913, of the large variety of corrosion-, oxidation-, and heat-resisting steels used today.

2. The only chromium-containing mineral of industrial importance is chromite, which is widely distributed throughout the world. Most of the deposits used as ores contain 40 to 55 per cent Cr_2O_3, 13 to 16 per cent FeO, 8 to 13 per cent Al_2O_3, 12 to 21 per cent MgO, and varying small amounts of SiO_2. The chromium-iron ratio should be greater than 3 to 1 and the silica should be low. The ores from Turkey and Southern Rhodesia are the most widely used in the United States.

3. Chromium metal for industrial use is made by the aluminothermic reduction of chromic oxide (Cr_2O_3) or by the reduction of chromic oxide by silicon in an electric furnace. Both products contain 98 to 99 per cent chromium and less than about 0.20 per cent carbon. Chromium metal made by aluminothermic reduction usually contains 0.2 to 0.9 per cent aluminum; when made by silicon reduction it contains 0.3 to 0.8 per cent silicon. Both products contain less than 1 per cent iron.

4. Chromium metal is used industrially in the manufacture of non-ferrous alloys, particularly for cutting and hard-facing alloys such as stellite, for electric-resistance heating elements of the nickel-chromium type, and for corrosion- and oxidation-resisting alloys.

5. High-purity chromium can be obtained by the reduction of high-purity chromium trioxide by a metallic reducing agent of the alkaline or alkaline-earth group. Calcium has been used successfully. Nearly all the high-purity chromium now made is deposited electrolytically. Chromium plating has developed rapidly since Fink outlined the necessary operating conditions and is widely used in decorative, wear-resistant, and corrosion-resistant applications.

6. Most of the published values for the physical properties of chromium were obtained on material of doubtful purity, or on material containing impurities whose effect was not known accurately. A résumé of the best available values is given in Table 3. As it is now possible to treat electrolytically deposited chromium to produce metal of very high purity, most of the physical constants should be redetermined.

7. Chromium is usually added to molten steel as a ferroalloy containing 65 to 72 per cent chromium. Many grades of ferrochromium are available, with maximum carbon percentages of 0.06 to 4.50. All of these grades are manufactured in the electric furnace. For the high-carbon alloys coke is the reducing agent, for the low-carbon alloys silicon or a silicon alloy such as ferrochromium-silicon is used. Until the development of the cheaper silicon-reduction process about 1905, most of the low-carbon ferrochromium used industrially was produced by an aluminothermic reduction similar to that used for chromium metal or by the ore-refining process, which yielded material with a low chromium content.

8. The addition to carbon steels of small or moderate amounts of chromium, usually as the high-carbon alloy, either alone or in combination with other alloying elements, results in increased hardness, tensile strength, ductility, and resistance to shock. It also tends to decrease grain size. These low- and medium-chromium and chromium-alloy steels, used widely for structural purposes, for tools, and in other similar special applications, are discussed in this first volume. The stainless and heat-resisting chromium and chromium-alloy steels, made by adding relatively large amounts of chromium—usually as the low-carbon ferroalloy—are a new chapter in ferrous metallurgy. These materials form the subject matter of the second and concluding volume of this monograph.

CHAPTER II

THE CONSTITUTION OF IRON-CHROMIUM ALLOYS

The High-temperature Portion of the Diagram—The Remainder of the Diagram—Authors' Summary

It is ordinarily safe to assume that the binary diagram for a given metallic system was first investigated in Tammann's laboratory, and the assumption is correct for the iron-chromium diagram. This work and several other early investigations are reviewed in this chapter because of their historical interest. It is now known that chromium has one of the highest melting points of the common alloying elements; *i.e.*, in the vicinity of 1900°C. Measurement of such temperatures was beyond the capability of early apparatus. It is also now known that high-purity chromium cannot be prepared by methods then available, consequently the first alloys, judged by modern standards, were very impure, and large errors can be introduced by even small amounts of impurity. Had the original workers on the system been aware of such difficulties, it is possible that they would not have made the attempt; yet, had the attempt not been made, it is likely that the incomplete knowledge of the iron-chromium diagram of today would be still less complete.

For convenience, existing information on the constitution of iron-chromium alloys is collected under several somewhat arbitrary headings. The first of these is the high-temperature portion of the diagram, by which is meant that portion which includes lines indicating liquid-solid equilibria.

A. THE HIGH-TEMPERATURE PORTION OF THE DIAGRAM

The aforementioned high melting point of chromium and the difficulty of preparing high-purity chromium supply sufficient reason to expect difficulty in the determination of the high-chromium portion of the diagram. The expectation is borne out, because it is in this region that diagrams constructed by the early workers show the greatest deviation from those resulting

from the most recent work. Gaps in knowledge still persist, but it is seen that violent future modification of the liquidus and solidus curves is improbable, although the chromium-rich end of the best pair available may be low by as much as 100°C.

19. Early Data on the Liquidus and Solidus.—The first report on the liquidus and solidus curves of the iron-chromium diagram, by Treitschke and Tammann,[42] appeared in 1907. Alloys were prepared from "low-carbon" iron and aluminothermic chromium containing 99 per cent chromium, 0.6 per cent iron, 0.5 per cent aluminum, and 0.2 per cent other elements. This analysis may be doubted. Arrests, obtained on cooling curves for the range 1600 to 600°C., are given in Fig. 1; these lead to liquidus and

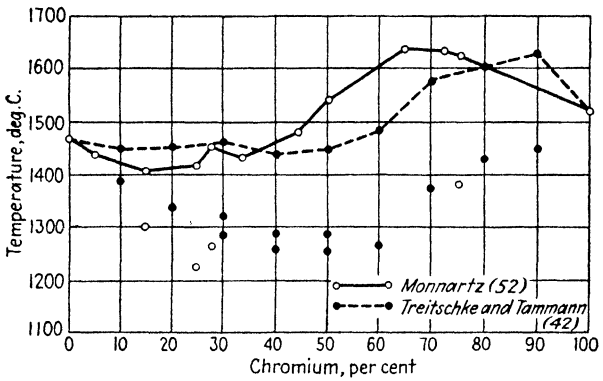


FIG. 1.—Liquidus and solidus of the iron-chromium diagram. (*Treitschke and Tammann*[42] *and Monnartz.*[52])

solidus curves of unusual shape. This fact, plus the observation of duplex microstructures, caused Treitschke and Tammann to postulate a compound of iron and chromium of low rate of formation. Superheated alloys (by the aluminothermic process), however, crystallized as homogeneous solutions, consequently it was concluded that the compound, iron, and chromium were completely intersoluble.

Four years later Monnartz[52] reported the measurements, on 21 alloys made by a modified thermit process, shown also in Fig. 1. Because of the temperature maximum in the vicinity of 66 per cent chromium, Monnartz assumed the existence of compound $FeCr_2$.

Jänecke[69] prepared alloys from hydrogen-reduced iron and aluminothermic chromium. Thermal analysis led him to con-

struct a diagram (reproduced in Fig. 2) showing a eutectic. Features of the liquidus that caused Treitschke and Tammann and Monnartz to assume the presence of compound formation

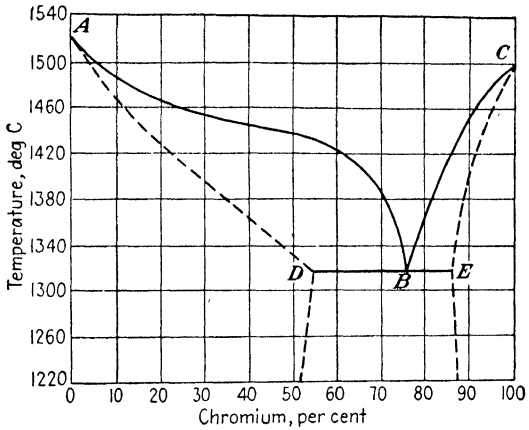


FIG. 2.—The iron-chromium diagram according to Jänecke.[69]

were ascribed by Jänecke to contamination by aluminum of their alloys.

Because of the conflict among the results of the foregoing investigations, Fischbeck[136] in 1924 attempted a correlation; he

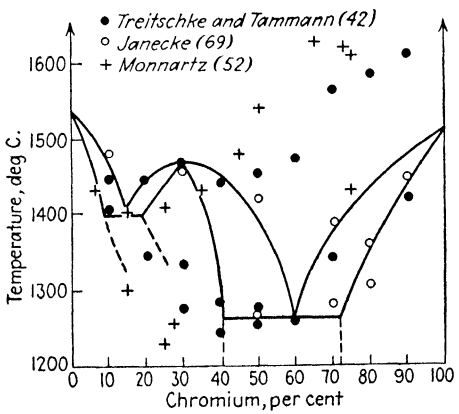


FIG. 3.—The iron-chromium diagram according to Fischbeck.[136]

concluded that the compound Fe_2Cr exists and that this compound forms eutectics with iron and chromium as is shown by Fig. 3. About the only value of this diagram is to show the state of knowledge in 1924.

20. Recent Data on the Liquidus and Solidus.—What may be termed the modern period in the development of the high-temperature iron-chromium diagram extends from 1925 to the present. It was opened by Pakulla and Oberhoffer,[168] who used a vacuum-melting furnace and materials of higher purity than those available to the early workers. They found a minimum between 10 and 15 per cent chromium to exist in the liquidus and solidus curves, as shown in Fig. 4. Because of experimental difficulty, no attempt was made to perform measurements on alloys containing more than 60 per cent chromium. The existence of a temperature minimum was confirmed by von Vegesack,[191] who placed it at 27 per cent chromium and 1490°C. (Fig. 5).

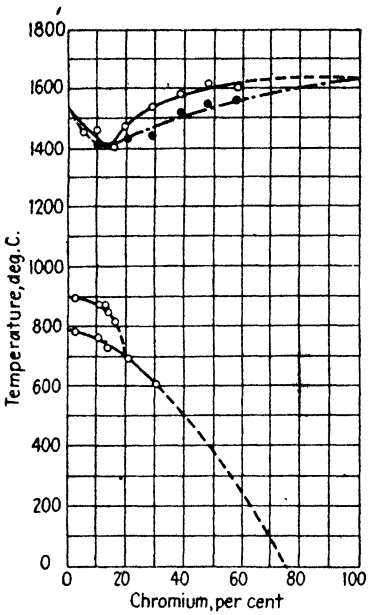


FIG. 4.—The iron-chromium diagram according to Pakulla and Oberhoffer.[168]

The most recent data on the liquidus and solidus of the iron-chromium diagram, determined by Adcock,[309] appeared in 1931. Alloys were prepared from hydrogen-annealed electrolytic chromium and iron in a vacuum in a high-frequency furnace. The alumina crucibles used were lined with thoria. The purity of the alloys is indicated by the following analyses of mixtures of turnings from various alloys:

Alloy mixture	Impurity content, per cent					
	C	S	N	Al	Si	Th
Low-chromium	0.04	0 01	0.003	Nil	0.004	Nil
High-chromium	0.03	0 01	0 007	Nil	0.002	Nil

The liquidus was determined by cooling the melt in the induction furnace; a thermocouple was used for all alloys except those rich

in chromium, for which an optical pyrometer was used. The temperature minimum found at 1507°C. differed from that of Pakulla and Oberhoffer (1400°C.) but was in fair agreement with that of von Vegesack (1490°C.). The melting point of chromium was found to be 1830°C. as compared with 1570 to 1650°C. for

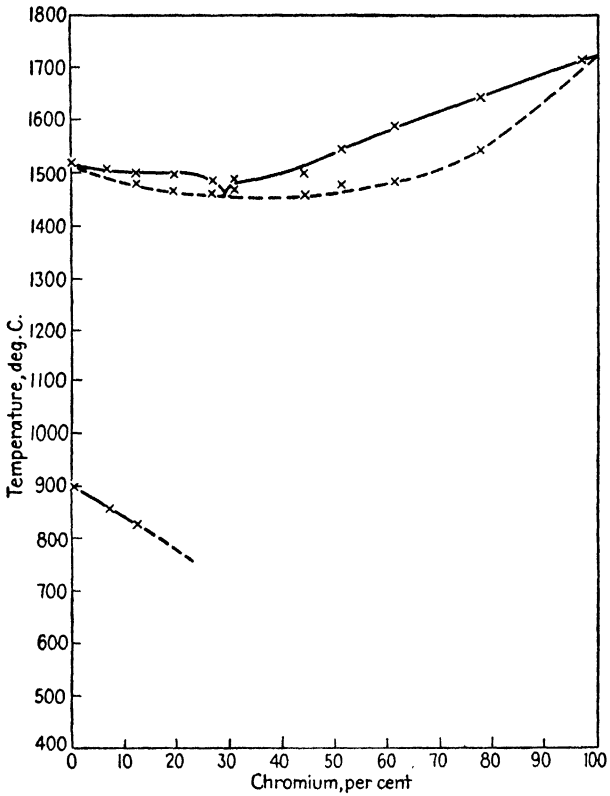


FIG. 5.—The iron-chromium diagram according to von Vegesack.[191]

chromium contaminated by nitrogen. Other values for this point are: Smithells and Williams'[260] 1920°C., Müller's[296] 1805°C., Hoffmann and Tingwaldt's[328] 1765 to 1800°C., and Friemann and Sauerwald's[320] 1915 to 1925°C. The solidus was determined by thermal analysis upon heating of alloys containing 0 to 70 per cent chromium. These data are assembled in Fig. 6; it is to be seen that the temperature interval between the liquidus and solidus is narrow to the left of the temperature minimum and

relatively wide to the right. The latter was confirmed by microscopic examination of chromium-rich alloys which had been cooled in the crucible, for strongly cored structures were found.

Differences between the high-temperature curves of Adcock and of Pakulla and Oberhoffer are marked, but because of the greater purity of the former's alloys and the more careful technique it may be concluded that Adcock's results are the most reliable available. The melting point of chromium should be established definitely, however. The concordance of the values of Smithells and Williams (1920°C.) and of Friemann and Sauerwald (1915 to 1925°C.) may be significant; further, the extrapolated curve for alloys containing 70 per cent chromium and

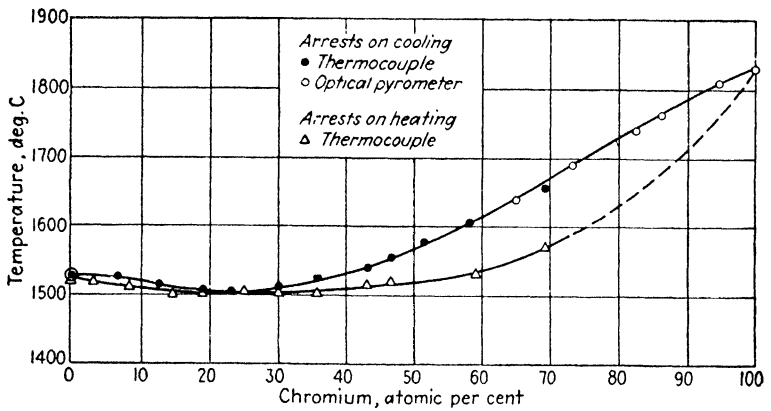


FIG. 6.—Liquidus and solidus of the iron-chromium diagram. (*Adcock.*[309])

0.02 to 6 per cent carbon indicates a liquidus temperature in excess of 1700°C. for a carbon-free 70 per cent chromium alloy.*

B. THE REMAINDER OF THE DIAGRAM

The iron-rich side of the iron-chromium diagram contains a "gamma loop" of the now well-known form.† This means that, beyond a certain chromium content, only alpha-phase alloys exist. Included also in this portion of the diagram, to conform with custom, is the temperature of magnetic inversion.

The remaining region of interest includes the compound of iron and chromium. Ordinarily the history of the development of a

* Kinzel and associates, unpublished data.

† For a short history of the development of the gamma loop, see "The Alloys of Iron and Silicon,"[389] page 61.

ferrous binary diagram includes the discovery of too many compounds, but this is not true of the iron-chromium diagram; even a modern investigator could find no evidence for the compound (the probable reason for this is given in the proper place).

21. The Gamma Loop.—The existence of the gamma loop in the iron-chromium diagram was discovered by Bain[176] in 1926. The investigation consisted principally of microscopic examination of alloys of ingot iron and low-carbon ferrochromium, although ambiguous results were supplemented by hardness measurement and X-ray analysis. These measurements indicated a maximum solubility of chromium in the gamma phase of some-

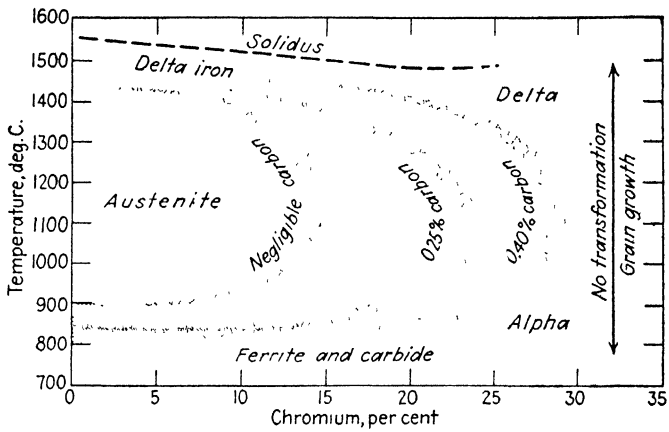


FIG. 7.—Effect of carbon on the gamma loop. (*Bain.*[176])

thing less than 15 per cent, as is shown by Fig. 7. The existence of the loop was confirmed by Oberhoffer and Esser[204] and by Kinzel.[219] Results of the former, obtained by an X-ray method, are given in Fig. 8; the indication of a temperature minimum should be noted. Since the X-ray method was unsatisfactory for the range 1250 to 1350°C., differential thermal analysis was used for the remainder of the loop. All the results of Oberhoffer and Esser are summarized in Fig. 9; the boundary *DEFG* was constructed by drawing a smooth curve through the experimental points. The other boundary, required by the phase rule, was drawn hypothetically. Kinzel used a special dilatometric method on wires containing less than 0.01 per cent carbon. The limit of existence of gamma phase was found to be 12.2 per cent chro-

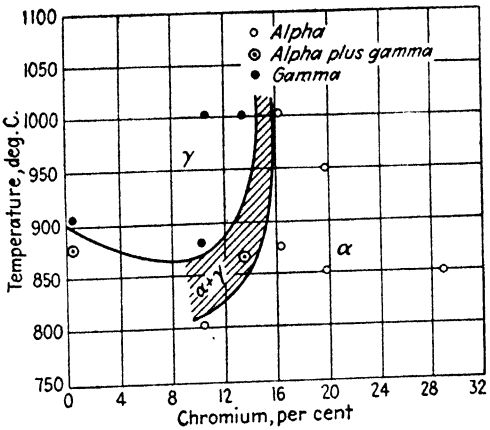


FIG. 8.—X-ray determination of the gamma loop by Oberhoffer and Esser.[204]

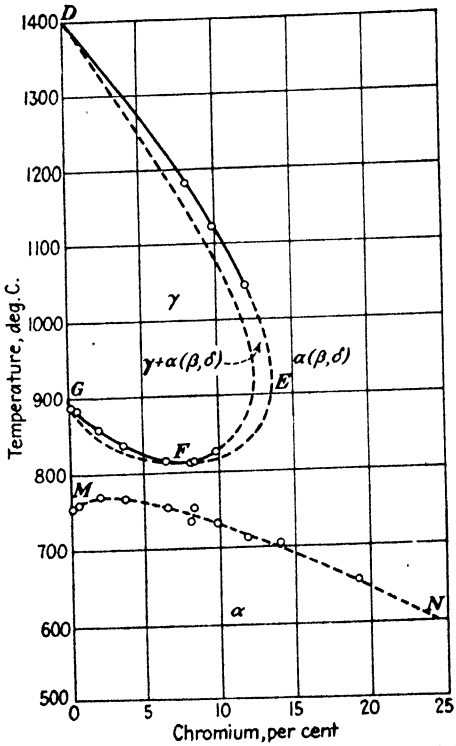


FIG. 9.—The complete gamma loop. (*Oberhoffer and Esser.*[204])

mium, but the lower boundary (Fig. 10) indicates an error of unknown origin.

Adcock[309] determined the gamma loop for his high-purity alloys chiefly by thermal analysis in a vacuum, and partly by dilatometric analysis. Results, summarized in Fig. 11, show good agreement between the two methods. Gamma phase was found to exist in an alloy containing 11.1 per cent chromium, but not in one containing 11.8 per cent; the limit of its existence was therefore placed at 11.5 per cent chromium. Indication of somewhat higher solubility of chromium in the gamma phase was found by Hicks[424] during the course of some diffusion measurements. Values of 7.5 at 1350°C. and 14 per cent chromium at

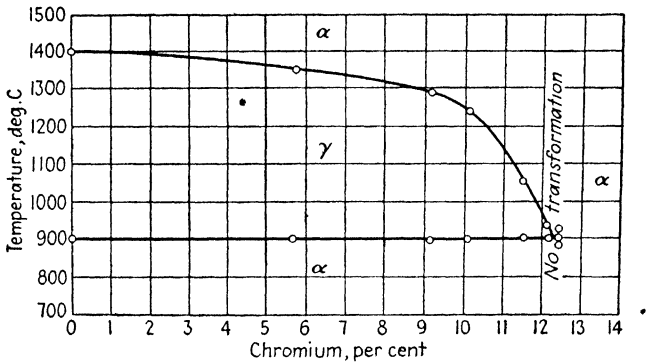


FIG. 10.—The gamma loop as determined by Kinzel.[219]

1200°C. were found. Indication of somewhat greater solubility of chromium was found also by Maurer and Nienhaus[225] by thermal analysis of alloys containing not more than 0.03 per cent carbon. These data are given in Fig. 12. Stäblein,[302] however, found dilatometric evidence of transformation in an alloy containing 11.3 per cent chromium, but not in one containing 12.6 per cent.

Experimental indication of the required two-phase region bounding the gamma loop was found dilatometrically by Bain and Aborn.[466] An important finding of the investigation was that only transformations detected on heating are reliable. This was confirmed by Austin and Pierce,[446] who used the same alloys (they contained 3 to 10.5 per cent chromium and less than 0.03 per cent carbon). Their data are given in Fig. 12, together with those of others for comparison. The lack of agreement makes it useless

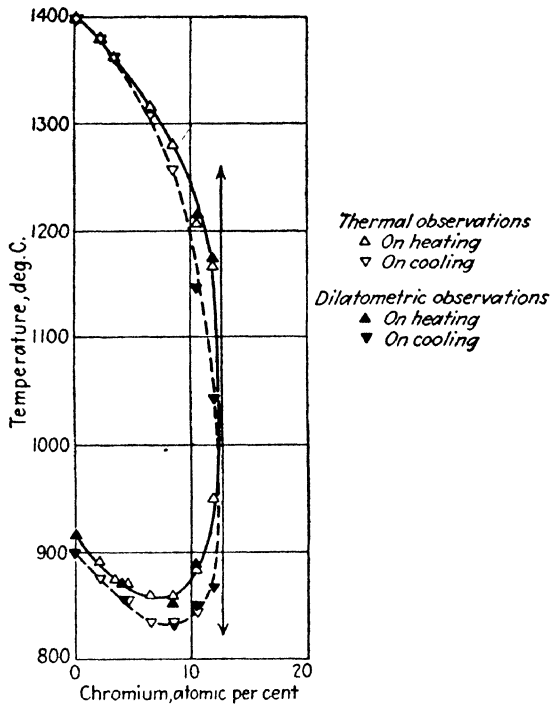


FIG. 11.—The gamma loop as determined by Adcock.[309]

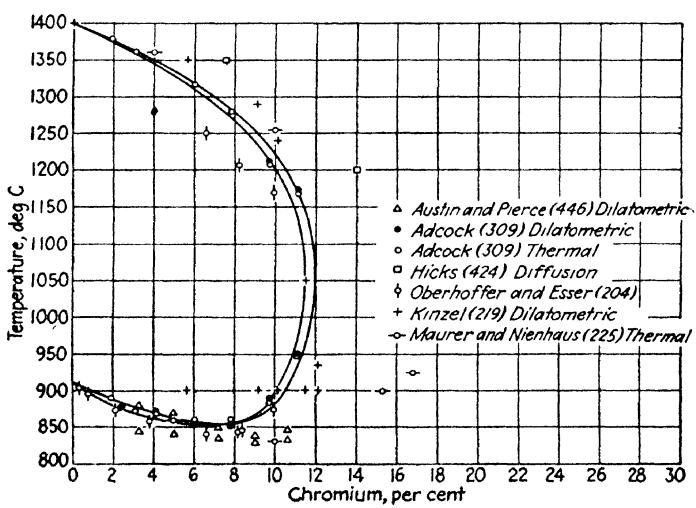


FIG. 12.—Summary of data on the gamma loop.

to attempt to locate the phase-region boundaries; those shown are to be considered semi-quantitative only. Most of the data indicate that the chromium content is less than 8 per cent for the temperature minimum. Those of Austin and Pierce, however, indicate a chromium content of more than 8 per cent. Evidently there is still need of work on this part of the diagram.

22. The Magnetic Inversion.—The temperature of magnetic inversion passes through a small maximum as chromium content is increased from zero. This was indicated by Murakami[75] (as shown by Fig. 13), who reported the first thermomagnetic

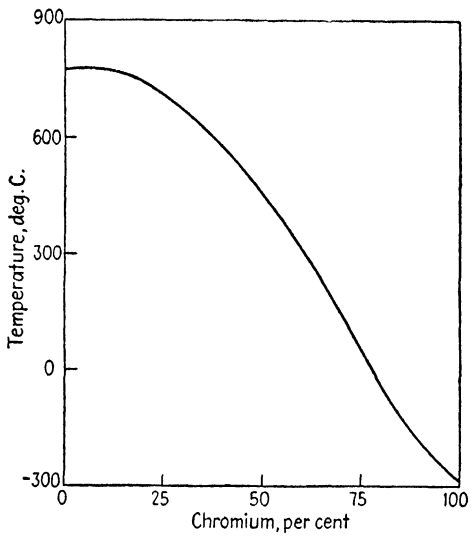


FIG. 13.—Magnetic change point of iron-chromium alloys. (*Murakami.*[75])

study of iron-chromium alloys in 1918, and shown clearly by Oberhoffer and Esser[204] (Fig. 9) and by Adcock[309] (Fig. 14). Disregarding temporarily Adcock's indication of complex behavior, it is to be seen that the Curie-point curve declines to absolute zero in the vicinity of 80 per cent chromium. Such behavior could be predicted, since chromium is not ferromagnetic.

As is stated on page 30, there is no real need to include information on the magnetic inversion in a discussion of the iron-chromium diagram, because such a diagram is concerned with phases. It is the custom, however, to include this information (the practice began when the nature of the inversion was not understood).

23. The Iron-chromium Compound.—The first real indication of an iron-chromium compound came relatively late in the history of the diagram. In 1927, Chevenard[197] ascribed irregularity of the thermal-expansion curve of a 42 per cent chromium alloy to the presence of a compound. This fact, by itself, means little; in the same year, however, Bain and Griffiths[194] discovered a

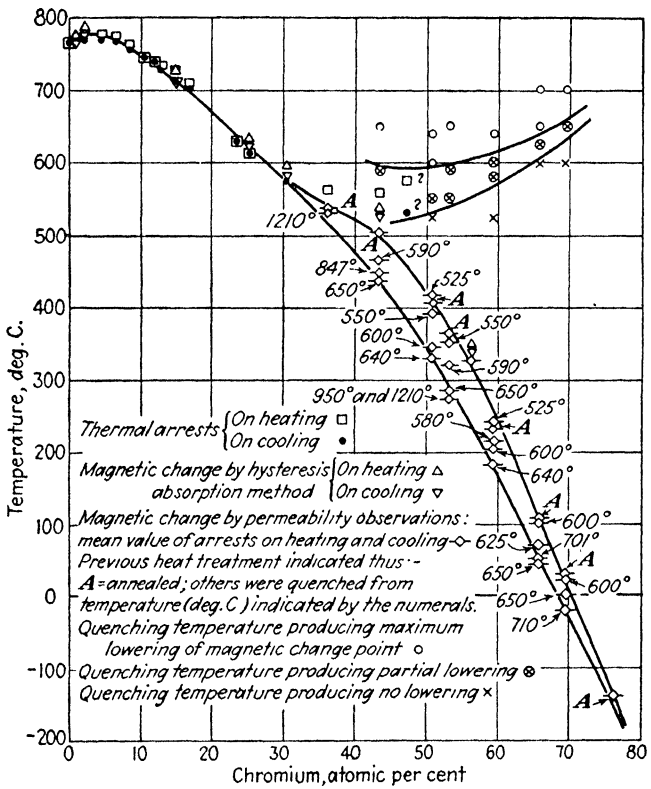


FIG. 14.—Magnetic transformations according to Adcock.[309]

compound-like constituent in iron-chromium alloys of about equal proportions, both with nickel present up to about 10 per cent and without nickel. They discussed the hardness, brittleness, and non-magnetic nature of the phase, its mode of formation, its temperature limits (885 to 970°C.) for various compositions, and the evident complexity of its crystal structure, as inferred from X-ray measurement. No indication of the new phase was found by Westgren, Phragmén, and Negresco,[236] because they reported

a continuous series of solutions characterized by small change of lattice dimensions. This left matters at a standstill until Wever and Jellinghaus[350] reinvestigated, by X-ray and microscopic methods, a series of alloys containing 40 to 60 per cent chromium, prepared from ingot iron and thermit chromium containing 98 per cent chromium, 0.98 per cent iron, 0.86 per cent aluminum, and 0.56 per cent silicon. After preparation for microscopic exami-

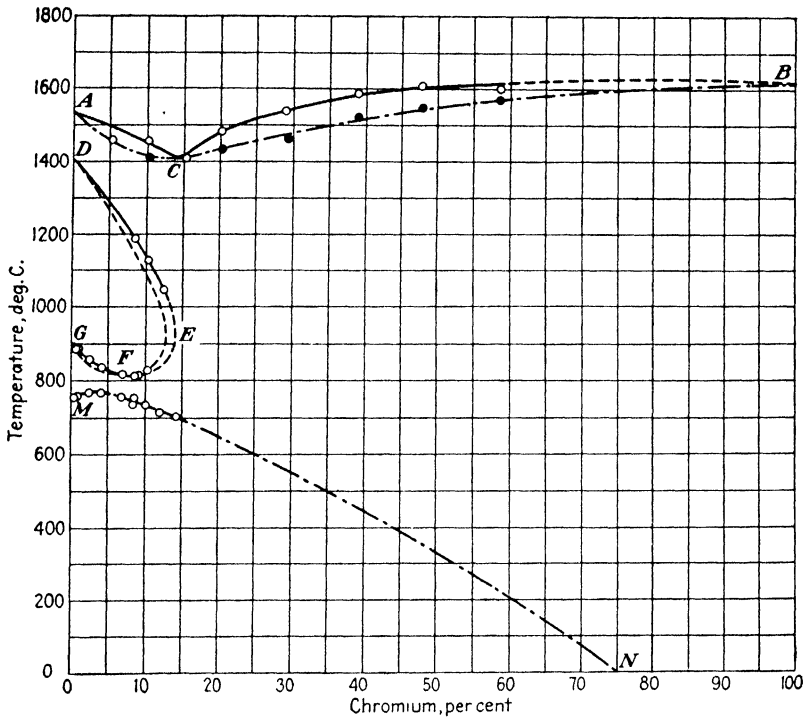


FIG. 15.—The Oberhoffer and Esser[204] iron-chromium diagram.

nation, an alloy containing 44.4 per cent chromium, as cooled from the melt, consisted of large polygonal grains with coarsely etched boundaries. No change was effected by annealing 1 hr. at 900°C. Annealing at 600°C. for 4 days produced markings similar to grain boundaries within the original grains. Definite evidence of a second constituent was obtained by a further anneal at 1200°C. for 5 hr., followed by quenching. Still further annealing at 1200°C. for 20 hr. caused restoration of the original structure, *i.e.*, the new constituent, precipitated at 600°C., was

redissolved at 1200°C. X-ray analysis of alloys containing 40 to 56.8 per cent chromium, annealed at 600°C. for 4 days, showed lines in addition to those of alpha phase. Wever and Jellinghaus accepted this as conclusive evidence for the compound and assigned the formula FeCr. Other evidence was obtained by thermal-expansion measurement, but not by electric-resistivity measurement. To account for the compound, the Oberhoffer and Esser diagram (Fig. 15) was modified, as shown by Fig. 16.

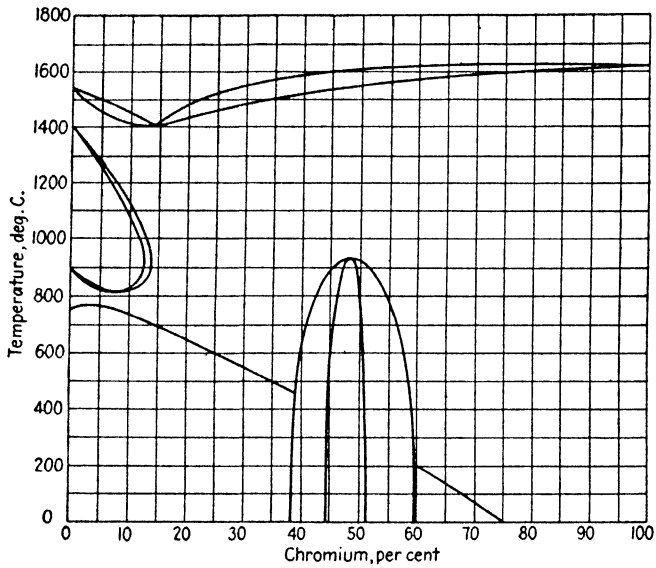


FIG. 16.—The Oberhoffer and Esser diagram modified by Wever and Jellinghaus.[350]

The results of Wever and Jellinghaus were denied almost at once by Adcock,[309] who measured the hardness, density, and electric resistivity of a series of high-purity alloys in addition to subjecting them to thermomagnetic and microscopic analyses. Determination of the lattice constants was made by Preston;[309] these are summarized in Fig. 17. Results of all methods of examination were interpreted to mean an uninterrupted series of solutions, as shown by Fig. 18 (the lines below 800°C. were associated with magnetic changes). To test the Wever and Jellinghaus conclusion that a compound is precipitated slowly at temperatures less than 900°C. in alloys containing about 50 per cent chromium, Adcock gave special treatment to alloys con-

taining 48.8 and 50.5 atomic per cent chromium; this consisted of vacuum annealing at 1300 to 1350°C. to remove coring, then annealing at 600°C. for 4 days in a silica bomb. Filings for X-ray examination were then annealed at 600°C. for 30 min. These details of treatment are worth remembering, because they play an important part in the story. At any rate, no new lines were found in the X-ray patterns; in addition, no change of lattice constant was effected by the special treatment. In addition, microscopic examination revealed no evidence of a new phase, but the evidence may have been there. Hardness tests gave no indication of the brittleness ordinarily to be expected in

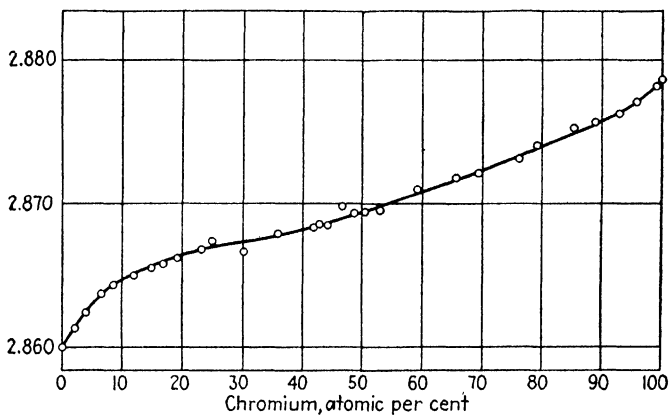


FIG. 17.—Lattice parameters of iron-chromium alloys. (*Preston.*[309])

the presence of a compound, but others[465,471] have shown that the first stage of precipitation has no significant effect on hardness. By annealing in nitrogen, Adcock was able to introduce new lines into the X-ray pattern; consequently he arrived at the conclusion that something of this sort was responsible for the results of Wever and Jellinghaus.

Adcock's evidence against the existence of a compound of iron and chromium was seemingly conclusive, but, perhaps in ignorance of it, Eriksson[417] reinvestigated a portion of the system. The alloys were evidently not so pure as those of Adcock, but this does not necessarily have an important bearing on the results, which were, in brief, that a new phase of complicated structure does exist, and that the new phase can be made to appear over a considerable range of composition; the limits were not established.

24. Recent Information on the Compound.—From the foregoing it is clear that the evidence to this point possibly favored the existence of the compound, but was inconclusive. Mean-

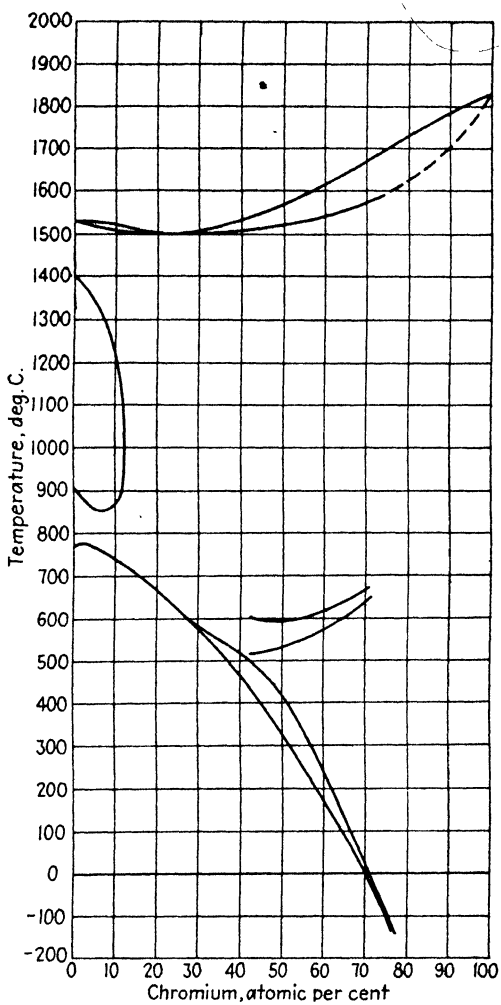


FIG. 18.—Iron-chromium diagram according to Adcock.[809]

while, in an X-ray investigation of the iron-chromium-silicon system, Andersen and Jette[465] had found a compound which yielded a diffraction pattern qualitatively similar to that reported by Wever and Jellinghaus for the compound FeCr. Further

work revealed the fact that, by proper treatment, the same pattern could be obtained for alloys containing equal proportions of iron and chromium and progressively less silicon. One alloy contained only 0.087 per cent silicon; its diffraction pattern was very different from that of alpha-phase alloys and bore no resemblance to that of any known nitride, carbide, or oxide of chromium. There seemed no doubt, therefore, that the new phase does exist in high-purity alloys of iron and chromium. To test this conclusion, further work was undertaken by Jette and Foote.[471]

TABLE 5.—EFFECT OF ANNEALING ON THE STRUCTURE OF IRON-CHROMIUM ALLOYS*

Alloy number	Phases present before annealing	Annealing		Degree of magnetism	Phases present after annealing
		Temperature, °C.	Time, hr.		
3†	Mostly σ	1049	18	Magnetic	α
4‡	α	904	18	Magnetic	α
4	σ	904	18	Magnetic	α
4	α	800	22	Magnetic	α
4	σ	800	22	Slightly magnetic	Mostly σ
4	α	775	44	Partly magnetic	$\alpha + \sigma$
4	σ	775	44	Non-magnetic	σ
71*a*§	$\alpha(\sigma?)$	767	3	.....	α
71*b*	$\alpha(\sigma?)$	773	16	.....	Mostly α
71*c*	$\alpha(\sigma?)$	775	86	.....	More σ than in 71*b*
4	α	756	44	Non-magnetic	σ
4	σ	756	44	Non-magnetic	σ
3	Mostly σ	717	141	Partly magnetic	Mostly σ
3	α	716	37	Slightly magnetic	Trace α
3	α	710	161	Non-magnetic	σ
4	α	600	48	Non-magnetic	σ

* Jette and Foote.[471]
† 0.006 per cent silicon, 50.3 per cent chromium.
‡ 0 003 per cent silicon, 52 4 per cent chromium.
§ 0.086 per cent silicon, 51.48 per cent chromium.

New alloys containing in the neighborhood of 50 per cent chromium were prepared from carbonyl iron and specially purified electrolytic chromium by vacuum melting. After a homogenizing anneal in hydrogen at about 1000°C. for 1 week, fine chips

were cut; these were sealed in evacuated quartz tubes and annealed at 700°C. for 5 days. This treatment converted the alloys almost completely into the new phase (called sigma). The results of other treatments are given in Table 5. The alpha-sigma transformation is evidently reversible. The direction of the transformation evidently changes between 775 and 800°C. in the neighborhood of 50 per cent chromium. No attempt was made to establish the homogeneity limits of sigma phase or the boundaries of the alpha-plus-sigma regions. Three factors were found to influence the transformation rate: (1) a possible stabilizing influence of silicon, (2) an accelerating effect of silicon, and (3) an accelerating effect of cold work.

Experiments with annealed ingots (duplicating Adcock's procedure) showed that annealing at 600°C. for 4 days would cause little or no precipitation of sigma phase; further, it was found that annealing the powders for 30 min. would barely start the precipitation. It was concluded that Adcock's alloys were "too pure and too well annealed" prior to the 600°C. treatment for transformation to take place in the time that was allowed. Thus, the matter of the iron-chromium compound seems to be settled permanently: a phase of complicated and unknown structure does exist in high-purity alloys of iron and chromium containing about equal proportions of these components, provided that a favorable heat treatment has been given.

C. AUTHORS' SUMMARY

1. Certain of the existing data were selected as more probable in order to construct the iron-chromium diagram given in Fig. 19. One liquid and three solid phases are shown.

2. The high-temperature portion of the diagram, involving liquid-solid equilibria, was constructed entirely from Adcock's data (pages 28 to 30), since, because of the purity of his alloys and because of the technique adopted, they should be the most reliable. There remains some question about the melting point of chromium, since there are indications that it is about 100°C. higher than that shown. If this is true, the right-hand portion of the pair of curves indicating liquid-solid equilibria should be lifted. The point is not very important, because it is reasonably certain that the curves are qualitatively correct, since all modern investigators of this portion of the diagram agree that iron and

chromium are completely intersoluble at temperatures immediately below those indicated by the lower—or solidus—curve. These investigators also agree that the curves pass through a common temperature minimum. Adcock's work places the minimum at about 1505°C. and 22 per cent chromium.

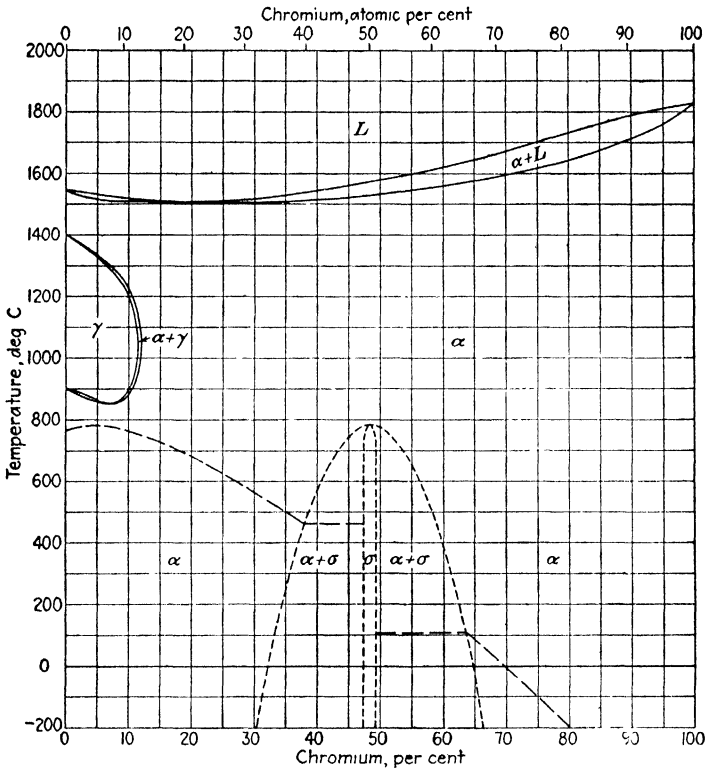


FIG. 19.—The proposed iron-chromium diagram.

The high melting temperatures of chromium-rich alloys and their susceptibility to contamination, *e.g.*, by nitrogen, make difficult the kind of measurements required; it is likely, therefore, that the pair of curves given in Fig. 19 will not be adjusted by experimental work for some time. However, the status of this part of the diagram may be considered as satisfactory for all ordinary purposes.

3. The selected gamma loop, although to be regarded as semi-quantitative only, should not be far wrong. The maximum solubility of chromium in gamma iron is indicated to be about

11.5 per cent. The presence of impurity, such as carbon, increases rapidly the apparent solubility, consequently the solubility limit may be expected to decline somewhat as increasingly pure alloys become available. There is no doubt that the alpha-gamma boundaries pass through a common temperature minimum; Fig. 19 indicates that it lies at about 855°C. and 7 to 8 per cent chromium, although these values are none too trustworthy. It may be worth pointing out that this temperature minimum is in every way equivalent thermodynamically to that of the liquidus and solidus curves.

The solubility limit of chromium in gamma iron is important practically only in that it marks the end of the possibility of heat treatment that depends on alpha-gamma transformation. So far as this chapter is concerned, it is sufficient to state that the limit for commercial materials is greater than that shown by Fig. 19.

4. Unlike many compounds in other systems, indication of a compound of iron and chromium was discovered relatively late in the development of the diagram, and its existence was to be denied and affirmed several times before proof was presented that dispelled doubt. The chief experimental difficulty was the fact that the upper limit of existence of the compound is in the vicinity of 800°C. for high-purity alloys plus a rate of precipitation too small to permit any detectable amount of the compound (sigma) phase to appear during ordinary rates of cooling. The rate of precipitation is greater in less pure alloys, but these were open to the argument that the new phase might not belong to the iron-chromium system. Recent work proved that the phase truly belongs to the system; the formula FeCr has been assigned, but this is not certain. The complicated X-ray pattern has not been solved; however, a structure of low symmetry is indicated. The boundaries—or homogeneity limits, as the X-ray workers seem to prefer—of the sigma-phase region have not been established; this is true also of the other boundaries of the alpha-plus-sigma region. It is known only that sigma phase appears over a relatively wide range of concentration. The sigma-phase region of Fig. 19 is therefore purely qualitative, except for the fact that the placing of the upper limit was guided by the best available experimental information. Considerable careful work probably will have to be performed before this portion of the diagram is determined.

5. In retrospect, it is easy to be convinced that several peculiarities of iron-chromium alloys are to be ascribed to the sigma phase. For example, inspection of the lattice constant versus composition curve for alloys not treated to produce sigma phase shows positive deviation from rule-of-mixtures values on the iron-rich side and negative deviation on the chromium-rich side. For all other metallic systems on which there is information, deviation is either all positive or all negative. Without pursuing the matter, seemingly the only way to account for such behavior is tendency toward incomplete intersolubility in iron-rich alloys (the temperature minimum of the liquidus and solidus substantiates this) and tendency toward compound formation dominating in chromium-rich alloys. Similarly, the effect of heat treatment on the magnetic inversion (Fig. 14) is clearly not characteristic of simple solid-solution alloys.

6. The magnetic-inversion curves shown in Fig. 19 were included to conform with custom. They were drawn—somewhat arbitrarily so far as location is concerned—as dictated by the phase theory. That there is no experimental evidence of the horizontal portions is not surprising; there can be none until iron-chromium alloys are examined in the equilibrium condition, and it is unlikely that alloys will ever be prepared in this condition for temperatures less than perhaps 500°C.

7. To recapitulate, the iron-chromium diagram for temperatures greater than 800°C. is fairly well known, for it is almost certain that no qualitative changes will be made. It is to be expected, however, that the liquidus and solidus curves, especially for chromium-rich alloys, and the gamma loop will undergo a certain amount of adjustment. Below 800°C. and in the vicinity of equal proportions of iron and chromium a phase which may be the compound FeCr is precipitated provided that sufficient time is allowed at temperatures permitting appreciable atomic mobility. Location of the boundaries of the region of existence of this phase is likely to be a difficult task.

CHAPTER III

THE IRON-CHROMIUM-CARBON SYSTEM

The Chromium-carbon System and Carbides of the Ternary System—The Iron-chromium-carbon Diagram—Authors' Summary

The ternary diagram is now widely recognized as a useful item in study of alloy steels and cast irons. Often, however, there are not sufficient data to enable construction of such a diagram, but this is not true of the iron-chromium-carbon diagram. In spite of the existence of chromium carbides, which necessarily complicate the diagram, there has been enough work of a suitable nature to clarify the behavior of the alloys.

The starting point in the construction of a ternary diagram is the contiguous binary diagrams; of these, the iron-chromium diagram is discussed in the preceding chapter and the iron-carbon diagram has been discussed by Epstein[469]. The chromium-carbon diagram is examined here.

A. THE CHROMIUM-CARBON SYSTEM AND CARBIDES OF THE TERNARY SYSTEM

A compound of chromium and carbon was reported as early as 1856, when Sainte-Claire Deville[6] investigated the reduction of chromium oxide by excess carbon. This observation was confirmed by Sainte-Claire Deville and Debray[8] in 1859. By alloying chromium and carbon at high temperature, Moissan[20,22,24] was led to the conclusion that more than one carbide exists; he assigned the formulas Cr_4C and Cr_3C_2. It was not until 1918, however, that the first chromium-carbon diagram appeared.

25. Chromium-carbon Diagrams.—In 1918, Ruff and Foehr[76] proposed the schematic diagram given in Fig. 20; they denied the existence of Cr_4C, reported by Moissan,[22] and assumed Cr_5C_2, Cr_4C_2, and Cr_3C_2, all formed by peritectic transformation. In the same year, Murakami[75] examined a series of alloys microscopically; he favored Cr_4C and Cr_3C_2. The solubility of carbon in chromium was determined to be 0.6 per cent; a eutectic of

chromium and Cr_4C was assumed to exist at 1.7 per cent carbon. Westgren, Phragmén, and Negresco[236] performed X-ray measurements in addition to microscopic examination. The carbides found were: face-centered cubic Cr_4C, trigonal Cr_7C_3, and orthorhombic Cr_3C_2. On the basis of the most recent work, these findings were substantially correct. Another pertinent observation was that, upon freezing of an alloy of composition corresponding to that of Cr_4C, primary crystals of Cr_7C_3 were obtained

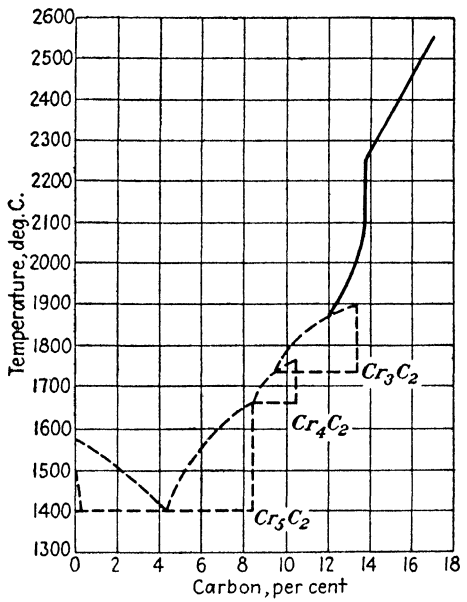


FIG. 20.—The chromium-carbon diagram. (*Ruff and Foehr.*[76])

with secondary crystals of Cr_4C inclosed in a eutectic of Cr_4C and chromium (at 3.3 to 3.6 per cent carbon).

Thermal and microscopic analyses and density measurements were performed by Kraiczek and Sauerwald;[290] these led them to assume the existence of Cr_5C_2 and Cr_3C_2. The former was supposed to undergo transformation at 1465°C. and to form a eutectic with chromium at 4.5 per cent carbon and 1485°C. These conclusions were denied by Westgren and Phragmén.[305] This evidently caused a reinvestigation by Friemann and Sauerwald,[320] and results this time agreed with those of Westgren, Phragmén, and Negresco as shown by Fig. 21. Dotted

lines indicate a metastable system Cr-Cr_7C_3, in agreement with the observation of low rate of precipitation of Cr_4C.

A different method of attack was pursued by Schenck, Kurzen, and Wesselkock;[341] *i.e.*, the "methane synthesis" method, which made use of the reaction

$$n\mathrm{Cr} + m\mathrm{CH} \rightleftharpoons \mathrm{Cr}_n\mathrm{C}_m + 2m\mathrm{H}_2$$

Results indicated Cr_5C_2 and Cr_3C_2. The method is not applicable to alloys of low carbon content and is evidently subject to errors in the higher carbon range.

A diagram having considerable plausibility was proposed by Hatsuta[326] as a result of thermal and microscopic analyses of a series of alloys (Fig. 22). Four carbides were found, *viz.*, Cr_4C,

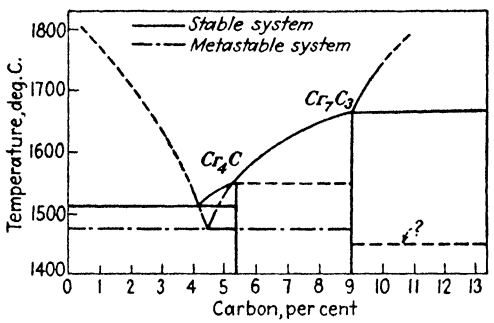


FIG. 21.—The chromium-carbon diagram. (*Friemann and Sauerwald.*[320])

Cr_7C_3, Cr_3C_2, and CrC. The eutectic of chromium and Cr_4C was placed at 1485°C. and 3.7 per cent carbon. The former value agrees with that of Kraiczek and Sauerwald and the latter with that of Westgren, Phragmén, and Negresco. Perhaps worth mentioning is the fact that the coincidence of points *D* and *N* is very improbable. (This construction is to be seen also in several of the preceding diagrams.) The transformation of Cr_3C_2 at 1505°C. was not found by the other workers, but the existence of such a transformation is plausible. The carbide CrC is entirely conjectural.

The form of the liquidus in the vicinity of the compound Cr_7C_3 is of considerable importance to the ternary diagram because it determines whether or not Cr_7C_3 can behave as a component of a quasi-binary section; if Cr_7C_3 results from peritectic transformation, there can be no quasi-binary section.

26. Carbides of the Chromium-carbon System.—The carbides of the chromium-carbon system, seemingly without question, are Cr_4C, Cr_7C_3, and Cr_3C_2. (According to Westgren[406] the carbide Cr_4C is really $Cr_{23}C_6$.) X-ray analysis of Cr_4C (or $Cr_{23}C_6$)

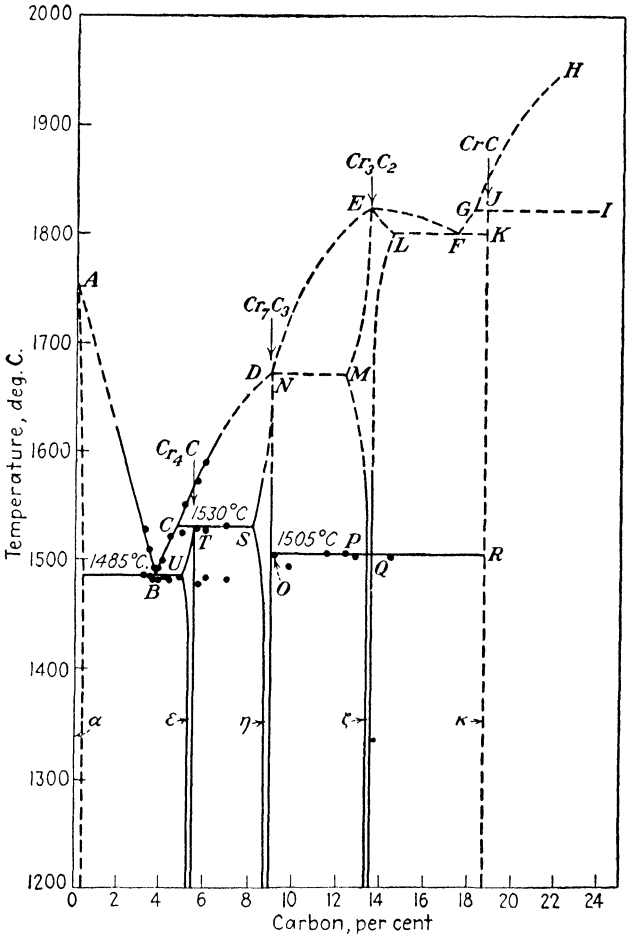


FIG. 22.—The chromium-carbon diagram. (*Hatsuta.*[328])

indicates that its structure is face-centered cubic, $a_0 = 10.638$ Å., with 120 atoms per unit cell. Cr_7C_3 is trigonal, base $a_1 = 13.98$ Å., altitude $a_3 = 4.523$ Å., with 80 atoms per unit cell. Cr_3C_2 is orthorhombic, $a_1 = 2.821$ Å., $a_2 = 5.52$ Å., $a_3 = 11.46$ Å., with 20 atoms per unit cell. Carbide CrC, proposed by Hatsuta, has not been isolated.

27. Carbides of the Iron-chromium-carbon System.—Behrens and Van Linge[21] in 1894 isolated a non-magnetic crystalline carbide from ferrochromium containing 13.3 per cent chromium and 5.5 per cent carbon by treating the alloy with acid. The composition of the residue corresponded to the formula $Cr_2Fe_7C_3$. From a 50 per cent ferrochromium alloy they obtained a carbide that was approximately Cr_3FeC_2. Carnot and Goutal,[25] by chemical separation, obtained from ferrochromium a residue having a formula $Fe_3C.3Cr_3C_2$, and another corresponding to $3Fe_3C.Cr_3C_2$ from 2 per cent chromium steels containing 0.57 and 2 per cent carbon. By heating a mixture of chromium oxide, iron, and petroleum coke in an electric furnace, Williams[27] obtained a carbide with the formula $3Fe_3C.2Cr_3C_2$. Arnold and Read,[51] by analyzing the residues extracted electrolytically from annealed chromium steels containing from 0.64 to 0.85 per cent carbon and 0.65 to 23.7 per cent chromium, concluded that the carbides varied with the composition of the steels. Their results are reproduced in Table 6. Murakami,[75] by means of magnetic and microscopic examinations, obtained evidence for $(Fe_3C)_{18}Cr_4C$, $(Fe_3C)_9Cr_4C$, and $Fe_3C.Cr_4C$.

TABLE 6.—ANALYSIS OF CARBIDES FROM CHROMIUM STEELS*

Composition of steel, per cent		Formulas corresponding to composition of carbide residue
C	Cr	
0 64	0 65	$20Fe_3C\ Cr_3C_2$
0 84	0.99	$12Fe_3C.Cr_3C_2$
0 835	4 97	$4Fe_3C.3Cr_3C_2.Cr_4C$
0 85	10 15	$Fe_3C.Cr_3C_2.Cr_4C$
0 88	15 02	
0 85	19 46	$2Fe_3C.3Cr_4C$
0 85	23 70	

* Arnold and Read.[51]

Edwards, Sutton, and Oishi[84] concluded that there exists in annealed chromium steel a double carbide having the formula $Fe_3C.Cr_3C_2$. When the amount of chromium present in the steels was less than that required to combine with the carbon to form this carbide, they found that none of the chromium existed

in solution in the iron, but when the amount of chromium was greater than was required to form $Fe_3C.Cr_3C_2$, some of the chromium, increasing with the total chromium content, remained in solution in the iron after the carbides had separated from the solution. In view of the fact that some of the chromium, in excess of that required for $Fe_3C.Cr_3C_2$, was found in the carbides and the rest was held in solution in the iron, they considered that the chemical nature of the carbide changed as the chromium increased, and that probably Cr_5C_2, capable of dissolving iron to a considerable extent, was also present when there was sufficient chromium in the steels.

From the analysis of the residue from a chromium-nickel steel containing 12 per cent chromium, 1 per cent nickel, and 2.6 per cent carbon, Russell[101] computed the formula FeCrC. After partial dissolution in hydrochloric acid and in aqua regia its analysis remained unchanged. From this behavior he concluded that the residue was a definite compound. Ehrensberger[106] reported analyses at Krupp of carbide residues extracted from armor plate. These results indicate Cr_4C_2, but this carbide is doubtful.

Residue analyses of six chromium steels containing about 2.2 per cent chromium and carbon from 0.36 to 1.62 per cent were made by Campbell and Ross[152] in 1925. The carbides were separated electrolytically. The results indicated that the carbides formed varied continuously in composition as the carbon increased.

Westgren, Phragmén, and Negresco,[236] by means of X-ray analysis, found that in annealed low-chromium steels almost all the chromium was contained in the cementite, $(Fe,Cr)_3C$, whereas the carbide present in stainless steels was cubic chromium carbide, Cr_4C, saturated with iron. In a steel containing 2 per cent carbon, 11 per cent chromium, and 1 per cent nickel, the carbide present was trigonal cubic carbide, Cr_7C_3, in which more than half of the chromium was replaced by iron. Ferrochromium with about 60 per cent chromium and 5 per cent carbon consisted principally of cubic chromium carbide, Cr_4C, in which the chromium was partially substituted by iron. Alpha metal and some trigonal carbide were also present in this alloy. In 1933, however, Westgren[406] stated that the carbide phase of a stainless steel containing about 13 per cent chromium and 0.3 per cent carbon

had the same crystal structure as the lowest of the chromium carbides, which from a calculation of the number of atoms in its unit cell had the formula $Cr_{23}C_6$ rather than Cr_4C, as he had previously assumed (see page 47).

These results, in the main, were confirmed by Wever and Jellinghaus[378] who, by X-ray analysis of isolated carbides, demonstrated that the carbide of chromium steels containing up to 2 per cent chromium possesses the crystal structure of cementite. In 3 per cent chromium steels they identified the trigonal carbide, Cr_7C_3, in addition to cementite. Divergent results were found by Maurer, Döring, and Buttig.[395] They analyzed carbides, isolated by chemical or by electrolytic treatment from steels containing 0.4 to 1.2 per cent carbon, 0.5 to 30 per cent chromium, and 0 to 5 per cent nickel. In steels containing less than 7 per cent chromium, they found that chromium existed in the mixture of carbides as Cr_3C_2, whereas in steels containing more than 7 per cent chromium, the chromium was present as Cr_4C_2. The carbides Cr_7C_3, Cr_5C_2, and Cr_4C were not found. Tofaute, in discussion of these results, stated that his analyses of residues from similar chromium steels agreed very well in chromium contents with those of Maurer and coworkers, but that he found the carbon contents to be lower. X-ray patterns indicated that the only chromium carbides present were Cr_4C and Cr_7C_3.

B. THE IRON-CHROMIUM-CARBON DIAGRAM

Despite the complexity of the iron-chromium-carbon diagram, it is established with unusual certainty for a ferrous ternary system by virtue of recent work. In one way the system is relatively easy to investigate, because chromium stabilizes iron carbide, hence there is no difficulty introduced by graphitization.

28. Early Information on the High-temperature Region of the Iron-chromium-carbon Diagram.—The first investigation of iron-chromium-carbon alloys was evidently conducted by Osmond[19] in 1892. It suffices to state that he recognized the possibility of complex carbide. The first investigation of the region of the melt was made by Goerens and Stadeler[40] who followed the course of the line of twofold saturation originating in the iron-carbon eutectic to about 8 per cent chromium, as shown by Fig. 23. Attempts to determine the variation of carbon solubility with chromium content at high temperature were inconclusive.

In 1923, Austin[117] undertook a general survey of the liquidus of a portion of the iron-chromium-carbon system from 0 to 50 per cent chromium and carbon up to the maximum permitted by the experimental conditions. Although a few alloys containing over 50 per cent chromium were prepared, chief attention was directed to those alloys containing from 0 to 20 per cent chromium. In preparing the alloys, Austin used ingot iron, low-carbon chromium, and crushed anthracite.

Figure 24 shows the effect on the liquidus temperatures of progressive additions of carbon to iron-chromium alloys containing 5, 10, 15, and 20 per cent chromium. Features noted by Austin were: (*a*) chromium up to 15 per cent had relatively little effect on the amount of carbon in the eutectic alloy, but with 20 per cent chromium the carbon content of the eutectic was lowered to slightly less than 4 per cent; and (*b*) an unexplained break occurred on the low-carbon side of the curve of the 80:20 iron-chromium alloy.

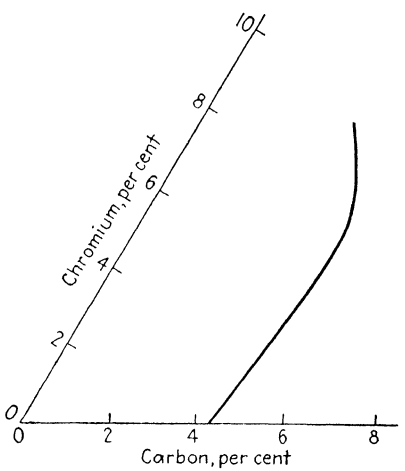


FIG. 23.—The effect of chromium on the position of the eutectic in the iron-chromium-carbon diagram. (*Goerens and Stadeler.*[40])

Figure 25 represents the effect of increasing carbon content on the freezing of iron-chromium alloys containing 30, 40, and 50 per cent chromium. From these curves Austin drew the conclusions that: (*a*) the freezing points of the alloys were lowered by the addition of carbon in amounts up to 2.5 per cent; (*b*) the carbon content of the eutectic was fairly constant and was considerably less than that of the eutectic in the 80:20 iron-chromium alloy; and (*c*) the course of the liquidus beyond the eutectic valley indicated some form of discontinuity.

Since Austin assumed that all three binary alloys formed eutectics, he suspected the formation of a ternary eutectic. Because of the absence of definite evidence for a ternary eutectic in the curves shown, he decided that the location of the ternary eutectic (if it existed) was in the vicinity of the binary iron-carbon

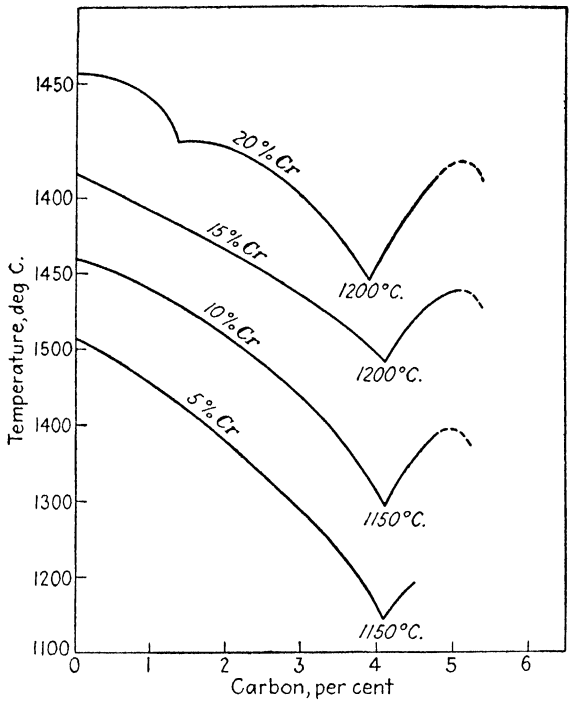


FIG. 24.—Liquidus of iron-chromium-carbon alloys of 5 to 20 per cent chromium. (*Austin.*[117])

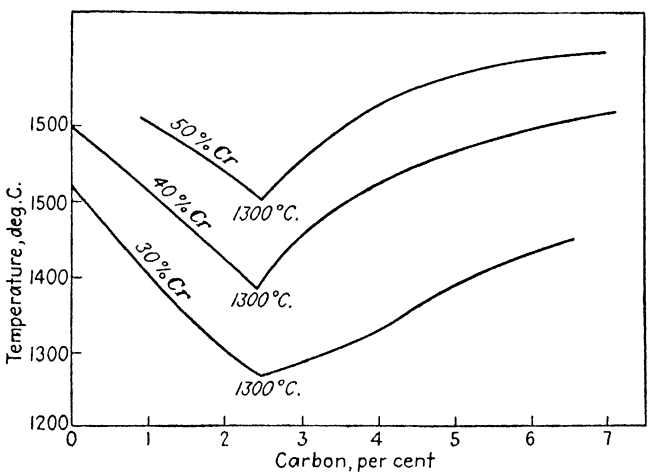


FIG. 25.—Liquidus of iron-chromium-carbon alloys of 30 to 50 per cent chromium. (*Austin.*[117])

eutectic. Therefore, he took a cooling curve of an iron-carbon alloy of eutectic composition, to which he afterwards added 2 per cent chromium. This caused a depression of 5°C. (9°F.) in the freezing point. Since this was in agreement with the results of

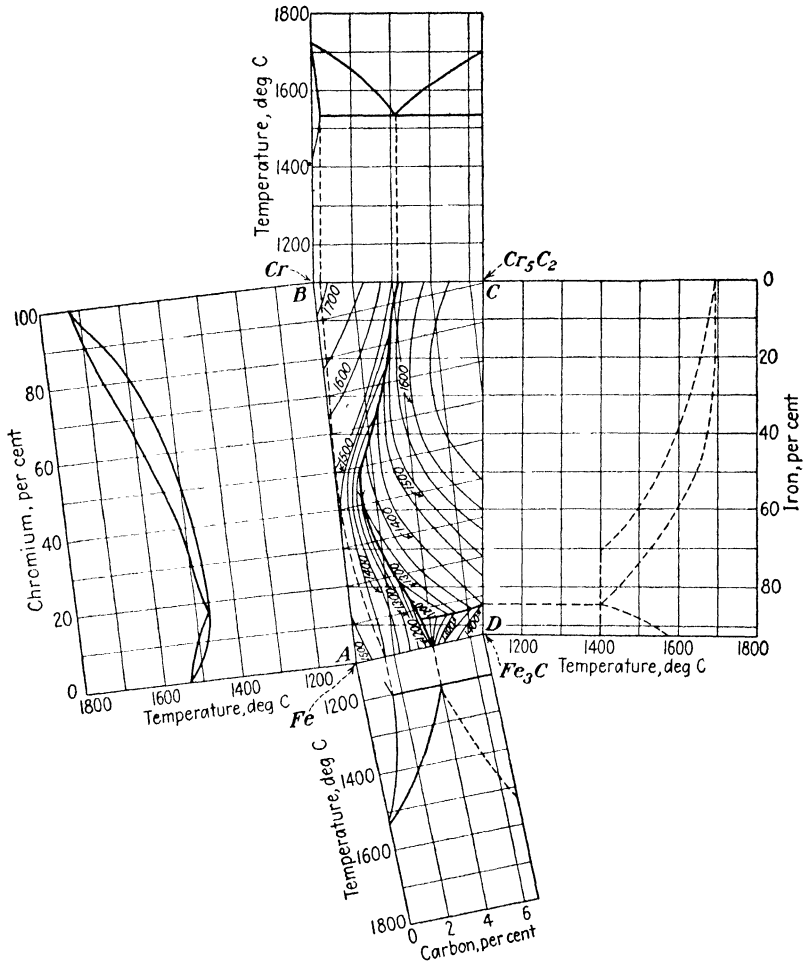


FIG. 26.—The iron-chromium-carbon diagram according to von Vegesack.(194)

Goerens and Stadeler for the liquidus of low-chromium alloys, he suggested that the system does contain a ternary eutectic, located very near the iron-carbon eutectic. Austin also considered that the differential etching effect that he observed in low-chromium alloys lent additional support to that suggestion.

29. Recent Data on the High-temperature Region of the Iron-chromium-carbon Diagram.—Von Vegesack[191] produced the diagram for the liquidus surface of iron-chromium-carbon alloys shown in Fig. 26. He investigated a number of alloys containing from 0 to 92.5 per cent chromium and 0 to 6.6 per cent carbon by means of heating and cooling curves. Supplementing his thermal study by microscopic examination, he was able to distinguish three types of primary solidification in the concentration region Fe-Fe_3C-Cr_5C_2-Cr. These are: (*a*) iron-chromium solid solution capable of dissolving carbon up to a certain amount; (*b*) cementite (Fe_3C) with little, if any, dissolved chromium; and (*c*) a solid solution of Cr_5C_2 in Fe_3C. The intersection of the three lines of doubly saturated melt was found to be at 3.6 per cent carbon and about 8 per cent chromium; its temperature was about 1090°C. on cooling and 1150°C. on heating.

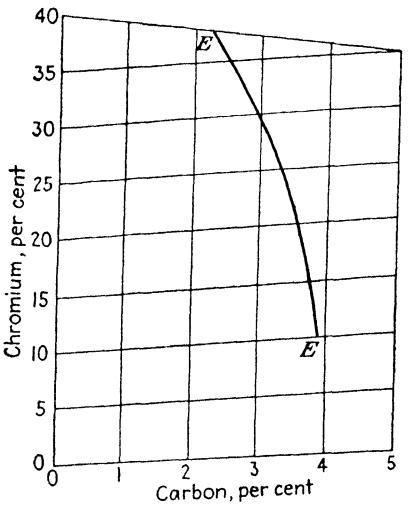


FIG. 27.—Course of the eutectic valley in the iron-chromium-carbon system. (*Valenta.*[304])

Friemann and Sauerwald[320] examined 24 iron-chromium-carbon alloys and found that the structures observed were all in accordance with those which might be predicted from von Vegesack's diagram. They considered, however, that a metastable equilibrium brought about by the slow formation of Cr_4C might also exist in the ternary system or, in other words, that Cr_4C might separate primarily if alloys in a certain narrow range of composition were cooled at a sufficiently slow rate.

Valenta[304] investigated the course of the eutectic valley in the iron-chromium-carbon system by the microscopic examination of a series of alloys and found it to be much the same as that determined by Austin; that is, the carbon contents of the eutectics were about 1 per cent higher than the values of von Vegesack. In addition, he found that with up to 20 per cent chromium the line of doubly saturated melt remained in the

region above 3.6 per cent carbon, and that only with higher chromium contents did it begin to move appreciably to the left, reaching 2 per cent carbon at 40 per cent chromium, as shown in Fig. 27.

A few data on the solubility of carbon in iron-chromium alloys at 1550 to 1700°C. were given by Lucas and Wentrup.[428] Values range from 8.4 to 10 per cent carbon for alloys containing 40, 60, and 80 per cent chromium.

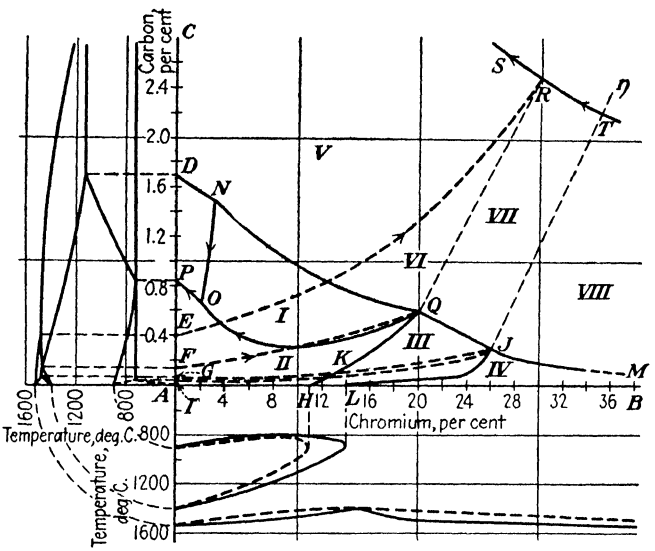


FIG. 28.—The iron-chromium-carbon diagram according to Murakami, Oka, and Nishigori.[252]

30. The Murakami, Oka, and Nishigori Diagram.—An iron-carbon-chromium diagram was deduced from the microstructures of quenched alloys by Murakami, Oka, and Nishigori;[252] this is given in Fig. 28. The fields marked by roman numerals were identified by them as follows:

I and II. Gamma phase upon solidification; upon further cooling, a carbide is rejected in I, and alpha phase is rejected in II.

III. Gamma or alpha phase, depending on carbon content.

IV. Alpha phase upon solidification; a carbide is rejected upon further cooling.

V and VI. Gamma phase in V; alpha phase which transforms to gamma phase by peritectic transformation in VI.

VII. Alpha phase upon solidification; it transforms to gamma phase by peritectic transformation; upon further cooling, the composition changes

along *QP* by rejection of carbide as the composition of alpha phase changes along *JI*.

VIII. Alpha phase upon solidification; eutectic is rejected upon further cooling.

Sections of Fig. 28 are given on pages 62 to 64.

Perhaps worthy of brief note is the iron-carbon-chromium diagram proposed by Valenta and Pobořil[403] on the basis of vari-

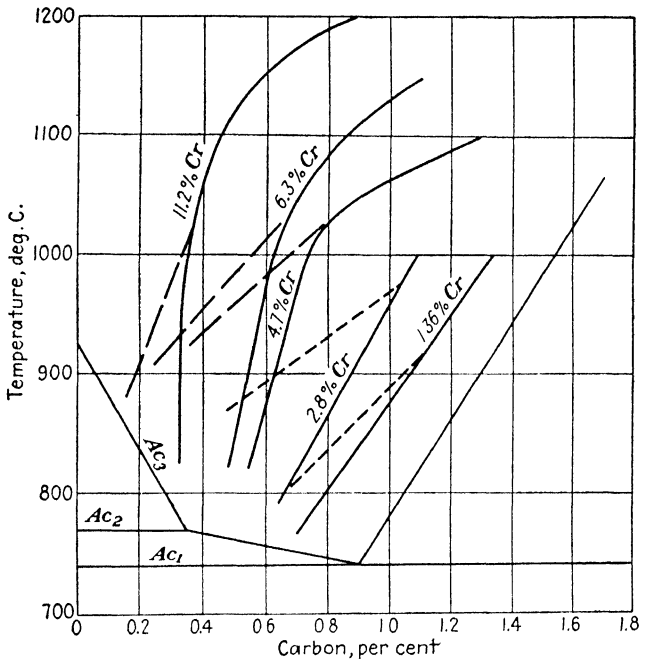


FIG. 29.—The influence of chromium on the solubility of cementite. (*Monypenny.*[89])

ous data of the literature, especially those of Westgren, Phragmén, and Negresco. This diagram differs from others mainly in that the compound Fe_7C_3 was assumed and that this compound forms a quasi-binary section with Cr_7C_3. Five non-variant equilibria are shown. There is, of course, no experimental evidence for Fe_7C_3.

31. Other Studies of the Iron-chromium-carbon Diagram.—The influence of chromium on the solubility of carbon in the gamma phase was studied by Monypenny;[89] results are given in Fig. 29. Full lines represent the disappearance of free carbide

upon heating, whereas the broken lines represent the disappearance of pearlitic carbide. This information enabled estimation of the course of the line of twofold saturation originating in the iron-carbon eutectoid (double saturation of gamma phase with alpha phase and carbide), as is shown in Fig. 30. Monypenny's investigation may be considered as modification of the iron-carbon diagram by the addition of chromium; modification of the

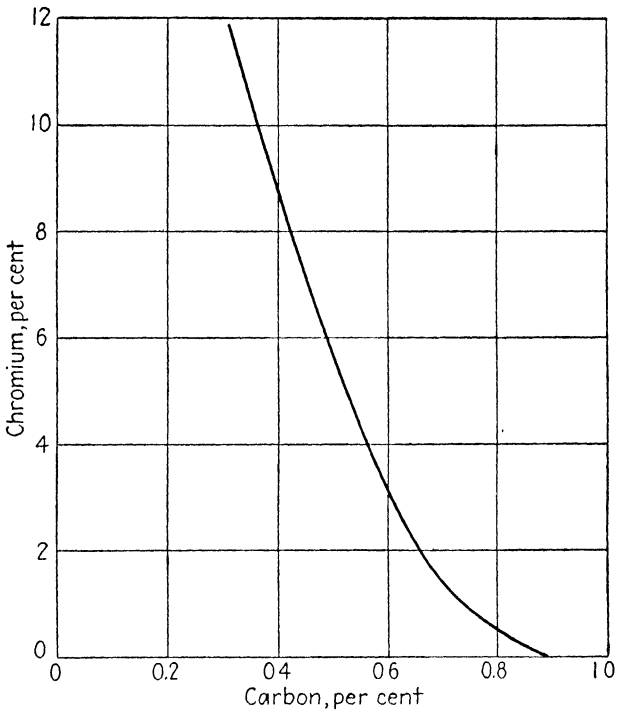


FIG. 30.—Influence of chromium on the eutectoid point. (*Monypenny.*[89])

iron-chromium diagram by the addition of carbon was studied by Bain[176] who found that, with 0.4 per cent carbon, the solubility of chromium in the gamma phase is about 25 per cent (see Chapter II).

Sections of the ternary diagram at 5, 10, 14, and 18 per cent chromium were constructed by Grossmann[198] from microstructures of quenched alloys. These sections show diminution of the gamma-phase area with increased chromium content and disappearance of the gamma phase in low-carbon, high-chromium

alloys. Such exploratory work is difficult to accomplish and the results are likely to require adjustment. In addition, the method used—that of study of the microstructures of small specimens quenched from increasing temperatures—is known frequently to yield ambiguous results. However, such work is

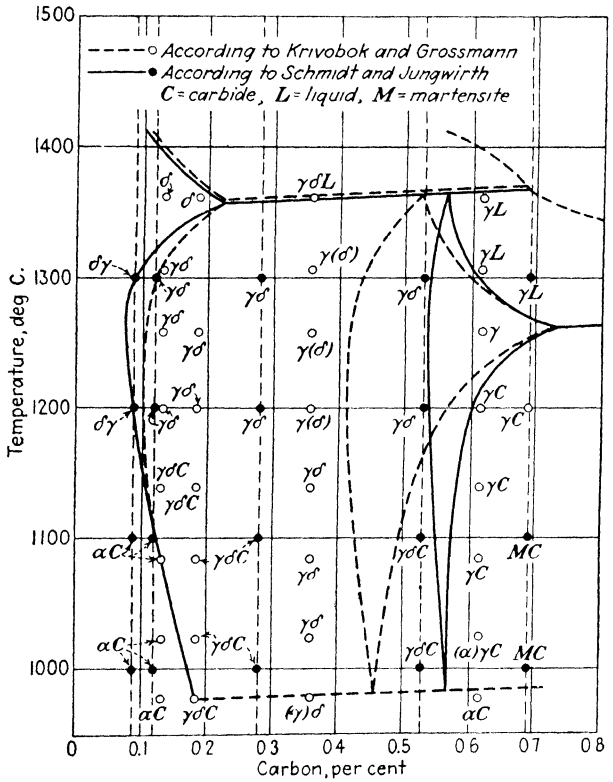


FIG. 31.—Modification of Krivobok and Grossmann's[291] diagram for 22 per cent chromium steels (*Schmidt and Jungwirth.*[342])

of great value in establishing the nature of the section; this is true of the sections at 22, 28, and 33 per cent chromium prepared by Krivobok and Grossmann.[291] Their results for 22 per cent chromium are given in Fig. 31, together with those of Schmidt and Jungwirth for comparison.

The important study of the phases of iron-chromium-carbon alloys conducted by Westgren, Phragmén, and Negresco[236] by X-ray and microscopic analyses identified the following phases:

1. Alpha phase.
2. Gamma phase.
3. Iron carbide, Fe_3C, capable of dissolving up to about 15 per cent chromium. The formula may thus be written $(Fe,Cr)_3C$.

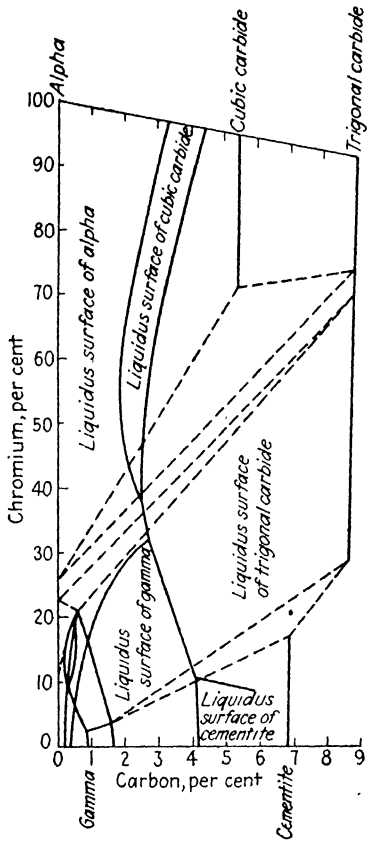


FIG. 32.—The iron-chromium-carbon system. Projection of the three-dimensional equilibrium diagram on the composition plane. (*Westgren, Phragmén, and Negresco.*[236])

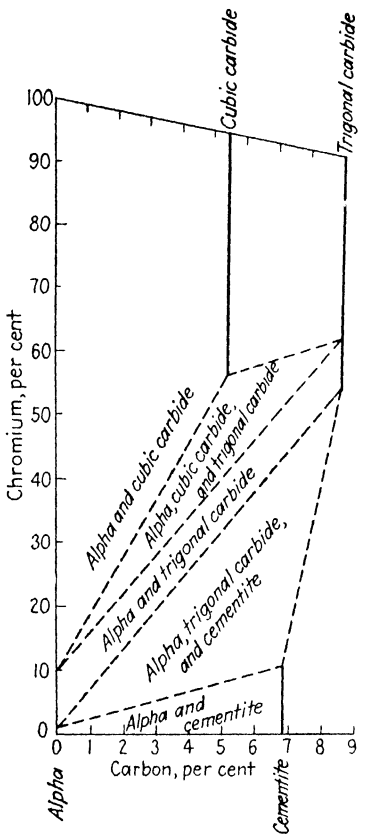


FIG. 33.—The iron-chromium-carbon system. Equilibrium at 700°C. (*Westgren, Phragmén, and Negresco.*[236])

4. Chromium carbide, Cr_4C, capable of dissolving iron up to about 25 per cent. The formula may thus be written $(Cr,Fe)_4C$.
5. Chromium carbide, Cr_7C_3, capable of dissolving iron up to about 55 per cent. The formula may thus be written $(Cr,Fe)_7C_3$.
6. Chromium carbide, Cr_3C_2, capable of dissolving iron to the extent of a few per cent only. The formula, however, may be written $(Cr,Fe)_3C_2$.

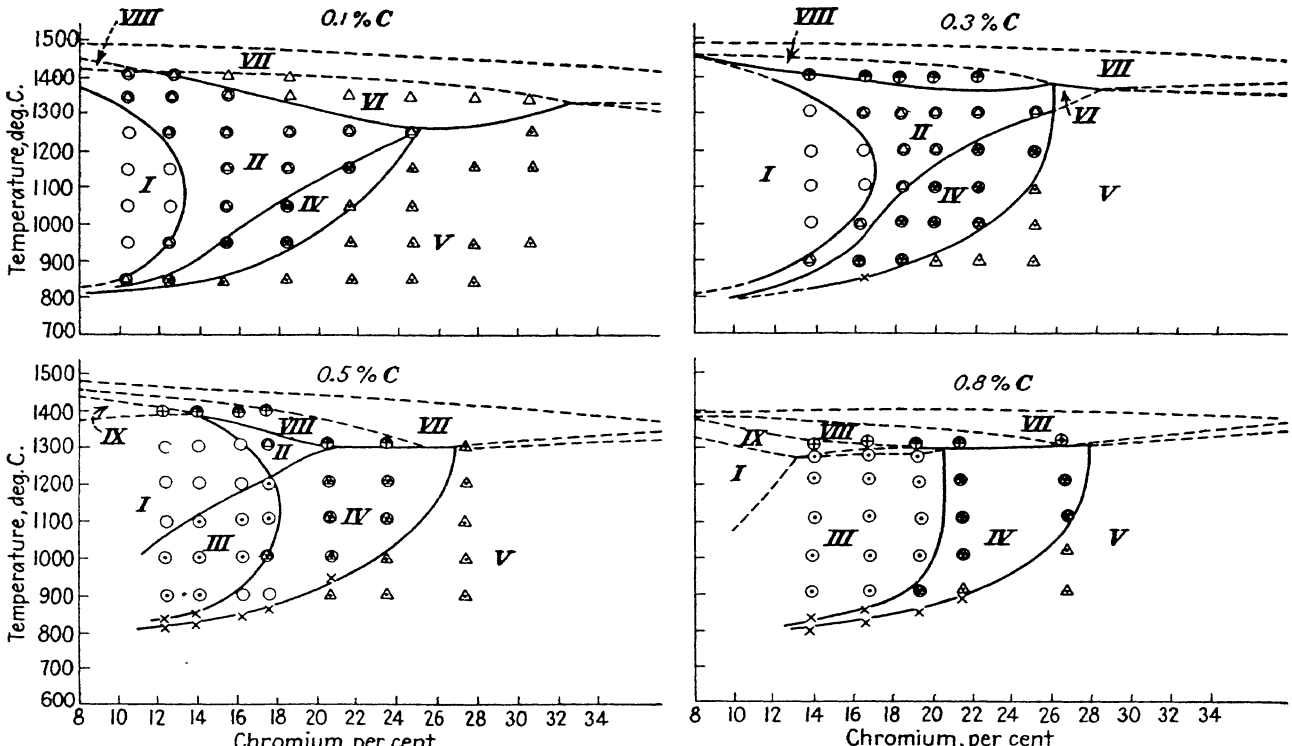


FIG. 34.—Sections of the iron-chromium-carbon diagram. Constant carbon contents. See Fig. 35 for interpretation of plotting points. (*Murakami, Oka, and Nishigori.*[252])

On the basis of these phases and the high-temperature measurements of von Vegesack (see page 56), Westgren, Phragmén, and Negresco constructed Figs. 32 and 33. The former is a projection

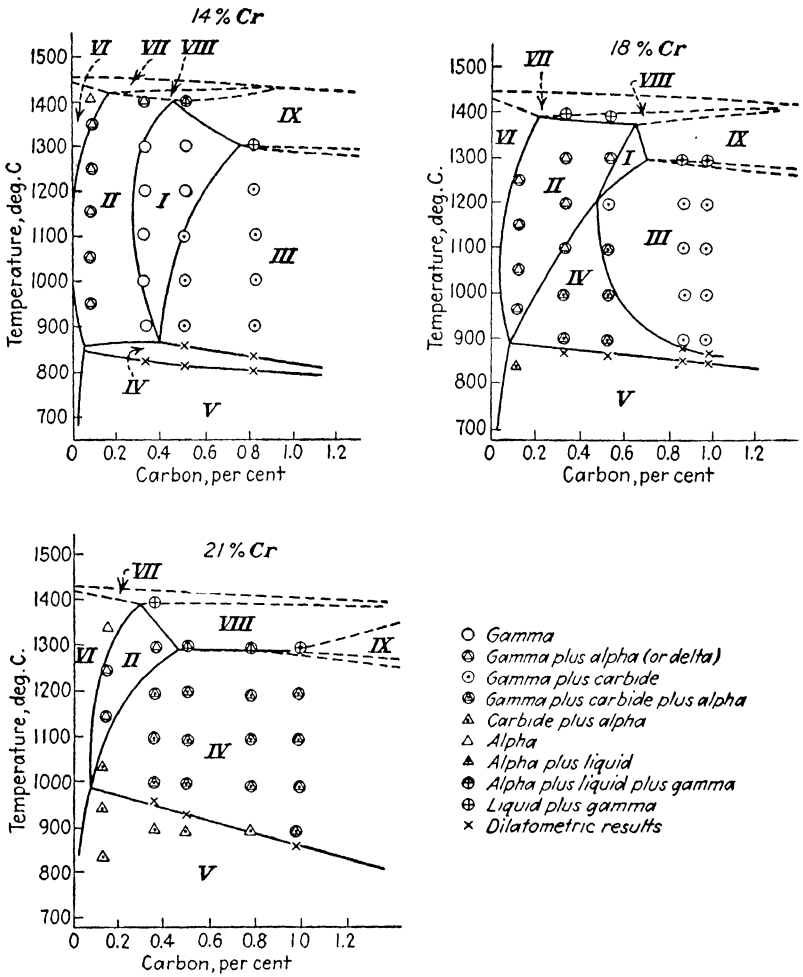


FIG. 35.—Sections of the iron-chromium-carbon diagram. Constant chromium contents. (*Murakami, Oka, and Nishigori.*[252])

upon the base of the prism, and the latter is an isothermic section at about 700°C. These diagrams may be regarded as the first, in the light of the current status of knowledge, to portray entirely correctly the behavior of iron-chromium-carbon alloys.

Sections of Fig. 28, the diagram of Murakami, Oka, and Nishigori,[252] are given in Figs. 34 to 36. The phases are identified in Fig. 35. These diagrams have been confirmed in part by subsequent work and must be considered in any comprehensive study of the system.

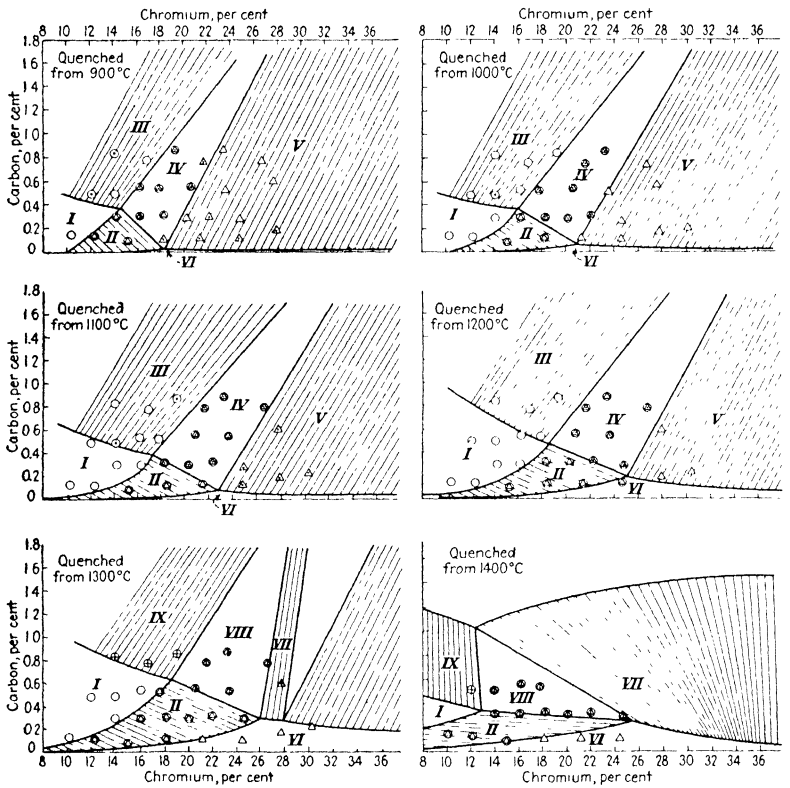


FIG. 36.—Isothermal diagrams of the iron-chromium-carbon system. See Fig 35 for interpretation of plotting points. (*Murakami, Oka, and Nishigori.*[252])

32. Investigations of Tofaute and Coworkers.—The most complete information on the iron-chromium-carbon system was supplied by Tofaute, Sponheuer, and Bennek[439] and by Tofaute, Küttner, and Büttinghaus.[476] The first investigation was concerned with alloys containing up to 1.5 per cent carbon and 12 per cent chromium. By means of dilatometric and microscopic studies, sections of the diagram were established. In interpreting the data, the phases reported by Westgren, Phragmén,

and Negresco were accepted. This procedure proved to be justified by a later report by Westgren.[459] Sections at 0.1, 0.4, 0.7, 1, and 1.5 per cent carbon are given in Fig. 37, and those at 1.6, 3, 5, and 8 per cent chromium in Fig. 38. These sections and those of the second investigation are self-explanatory.

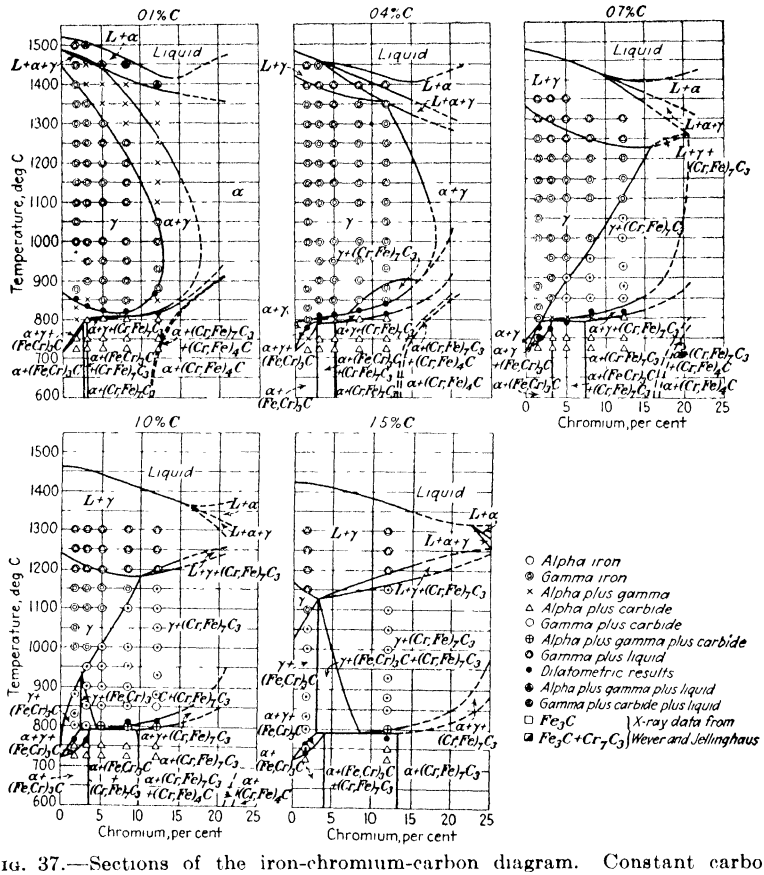


FIG. 37.—Sections of the iron-chromium-carbon diagram. Constant carbon contents. (*Tofaute, Sponheuer, and Bennek.*[439])

The second investigation, by Tofaute, Küttner, and Büttinghaus,[476] included alloys containing up to 70 per cent chromium. Sections of the diagram were constructed on the assumption of the existence of a quasi-binary section Fe_3C-Cr_7C_3 and from data obtained by thermal, microscopic, and X-ray analyses and by determination of several physical properties. It was further

assumed that four non-variant equilibria exist; these and their associated three-phase equilibria are given in Fig. 39. Starting from the uppermost temperature, the first of the four-phase equilibria, at about 1300°C., is of the transition type—the type that is most common in ternary systems of which iron and carbon

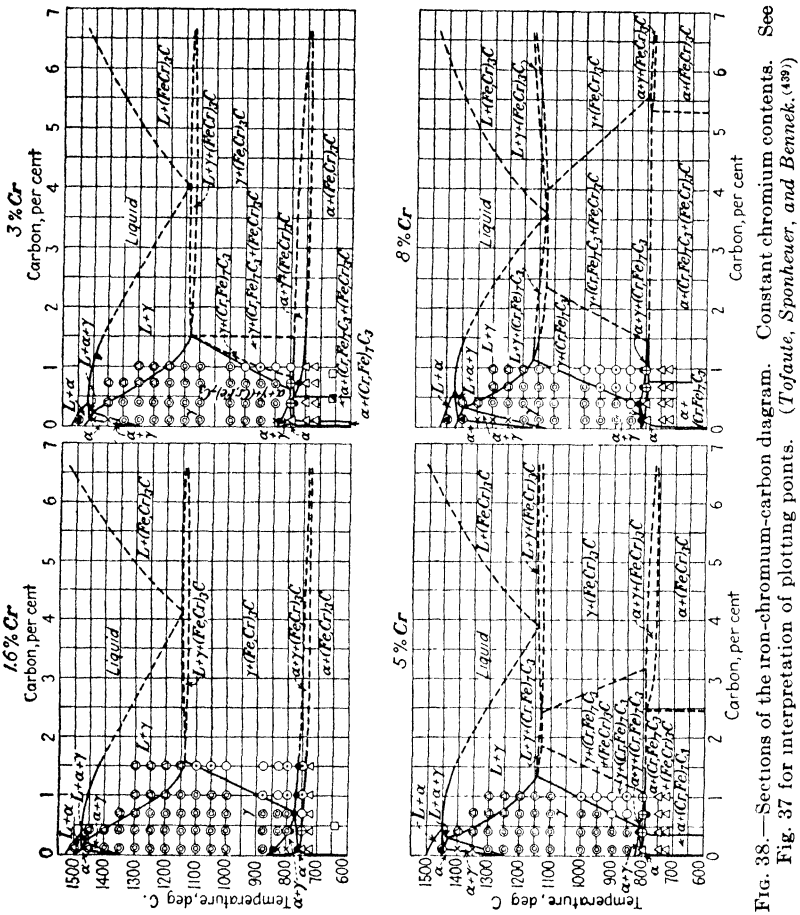


FIG. 38.—Sections of the iron-chromium-carbon diagram. Constant chromium contents. See Fig. 37 for interpretation of plotting points. (*Tofaute, Sponheuer, and Bennek.*[439])

are two components. Two three-phase equilibria approach the four-phase equilibrium from above; in this instance, the participants of one triad are the liquid and the two chromium carbide phases; the participants of the other are the liquid, alpha, and Cr_4C phases. Both triads originate in the Cr-Cr_7C_3 quasi-binary section. Below the four-phase equilibrium, the phases are

distributed in two new triads; one is composed of the liquid, alpha, and Cr_7C_3 phases, the other of alpha and the two carbide phases. The arrangement of the points representing triple saturation (necessarily at a constant temperature in a constant-pressure section of a ternary diagram) is shown schematically.

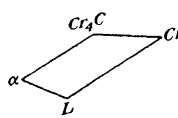
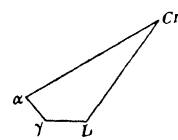
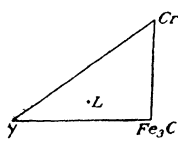
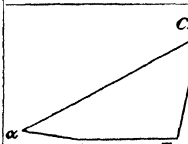
Three- and four-phase equilibria		Type of non-variant equilibrium	Point	Percentage C	Percentage Cr
I. 1300°C.					
$L + Cr_7C_3 + Cr_4C$	from Cr-Cr_7C_3		L	2 2	38 6
$L + \alpha + Cr_4C$	from Cr-Cr_7C_3		α	0 1	50
$L + Cr_4C + \alpha + Cr_7C_3$			Cr_7C_3	5 4	80
$L + \alpha + Cr_7C_3$	to II		Cr_4C	8 3	76
$\alpha + Cr_7C_3 + Cr_4C$	to IV				
II. 1260°C					
$L + \alpha + \gamma$	from Fe-C		L	2 4	30
$L + \alpha + Cr_7C_3$	from I		α	0 3	26
$L + \alpha + \gamma + Cr_7C_3$			γ	0 6	20
$L + \gamma + Cr_7C_3$	to III		Cr_7C_3	8 3	76
$\alpha + \gamma + Cr_7C_3$	to IV				
III. 1130°C.					
$L + \gamma + Fe_3C$	from Fe-C		L	3 6	8
$L + Cr_7C_3 + Fe_3C$	from Fe_3C-Cr_7C_3		γ	1 5	3
$L + \gamma + Cr_7C_3$	from II		Cr_7C_3	7 7	54
$L + \gamma + Cr_7C_3 + Fe_3C$			Fe_3C	6 7	15
$\gamma + Cr_7C_3 + Fe_3C$	to IV				
IV 790°C.					
$\gamma + Cr_7C_3 + Fe_3C$	from III		α	0 05	2 6
$\gamma + \alpha + Cr_7C_3$	from II		γ	0 7	2
$\gamma + \alpha + Cr_7C_3 + Fe_3C$			Cr_7C_3	9 7	62
$\gamma + \alpha + Fe_3C$	to Fe-C		Fe_3C	6 8	9 6
$\alpha + Fe_3C + Cr_7C_3$	to base				

FIG. 39.—Three-phase, four-phase, and non-variant equilibria in the iron-chromium-carbon system. (*Tofaute, Kuttner, and Buttinghaus.*[476])

The estimated coordinates of the points are given in the last two columns of Fig. 39. In a like manner the necessary information on the other four-phase equilibria is given. It is interesting to note that, of the four, three are of the transition-plane type; the fourth is of the eutectic type.

A schematic basal projection of the four-phase equilibria is shown in Fig. 40. This shows the locations of the three quad-

rangles and the triangle that represent the four-phase equilibria. Also shown are the lines of twofold saturation that originate in the planes of the binary sections. These lines of twofold saturation intersect in the aforementioned points of threefold saturation. The lines indicating doubly saturated liquid phase that intersect in the ternary eutectic are worthy of note, because

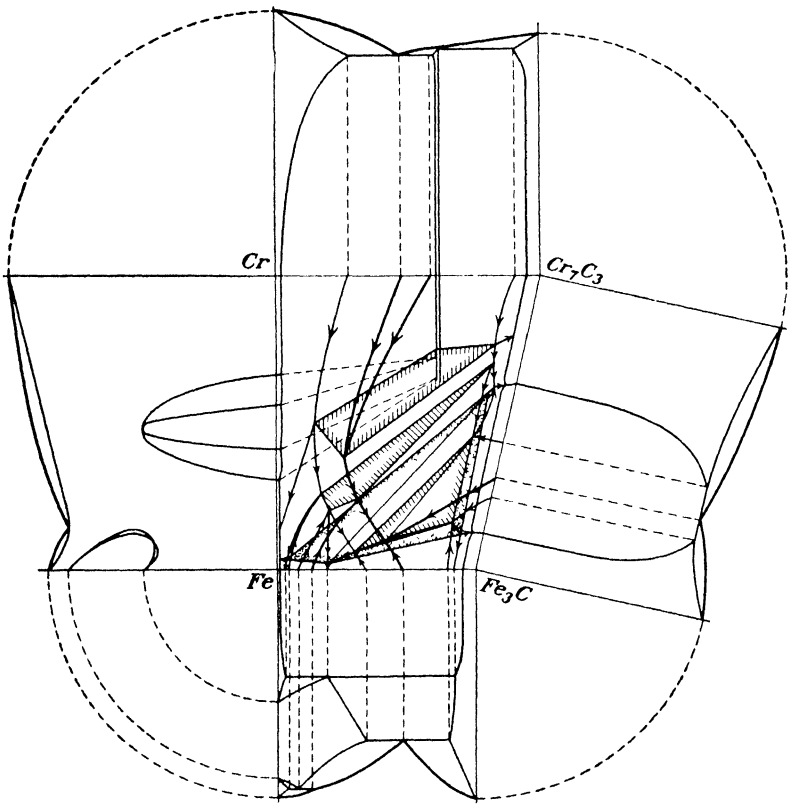


FIG. 40.—Schematic projection of four-phase equilibria. (*Tofaute, Küttner, and Buttinghaus.*[476])

the form of the intersection barely escapes thermodynamic implausibility. The angle between any two of the intersecting lines ordinarily must be less than 180 deg. Isothermic sections of the iron-chromium-carbon diagram at 1150, 850, and 20°C. are given in Figs. 41 to 43. These contain a minor error of principle in that several sides of several three-phase regions are not straight lines. To be noticed is the appearance of the com-

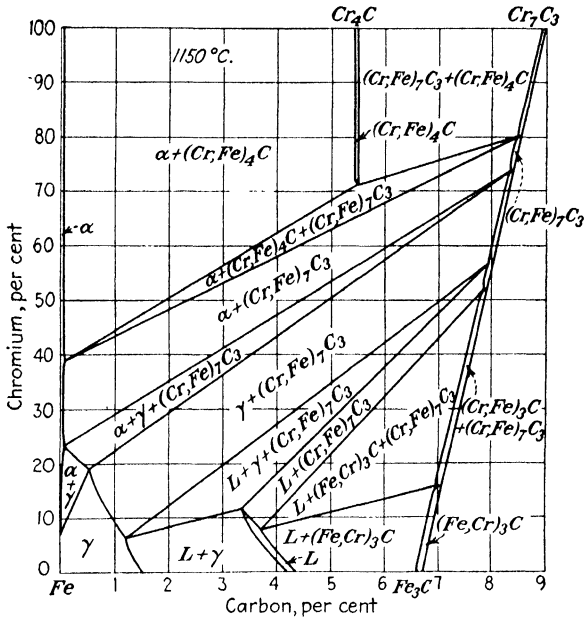


FIG. 41.—Isothermic section at 1150°C.(476)

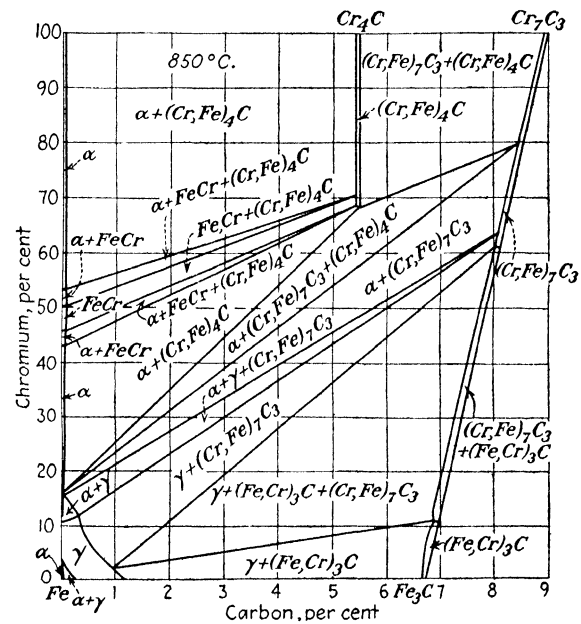


FIG. 42.—Isothermic section at 850°C.(476)

pound FeCr (discussed in Chapter II) in the vicinity of 50 per cent chromium at relatively low temperatures. That this phase appears in the ternary system was fully confirmed by X-ray analysis and measurement of saturation magnetization, residual induction, coercive force, electric resistivity, and hardness. The phase was detected also by microscopic examination.

33. Conclusions from Work of Tofaute and Coworkers.—X-ray examination of the carbide phases led to complete agreement with the conclusions of Westgren, Phragmén, and Negresco.

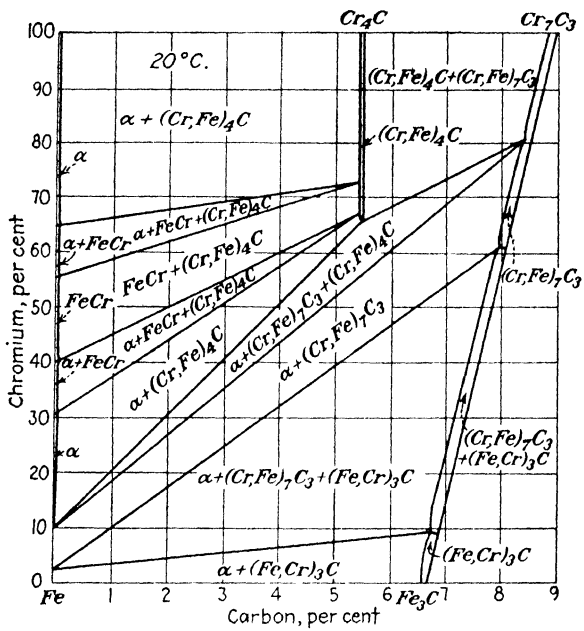


FIG. 43.—Isothermic section at 20°C.[47a]

Variations of lattice constants showed that the carbides are capable of dissolving considerable amounts of one or more of the components.

Vertical sections of the diagram are given in Figs. 44 to 52. Inspection of these and of Fig. 38 shows a progressive diminution of the gamma-phase area as the chromium content is increased from zero; it disappears between 15 and 20 per cent chromium (according to Tofaute, Küttner, and Büttinghaus, at 20 per cent). Several practical conclusions follow from these sections.

1. The 15 per cent chromium section (Fig 45) shows that the gamma-phase region is narrow; thus, the composition for full hardening by quenching is fixed within relatively narrow limits; further, the reason for quenching temperatures of 900 to 1000°C. for chromium cutlery steels is evident from this section.

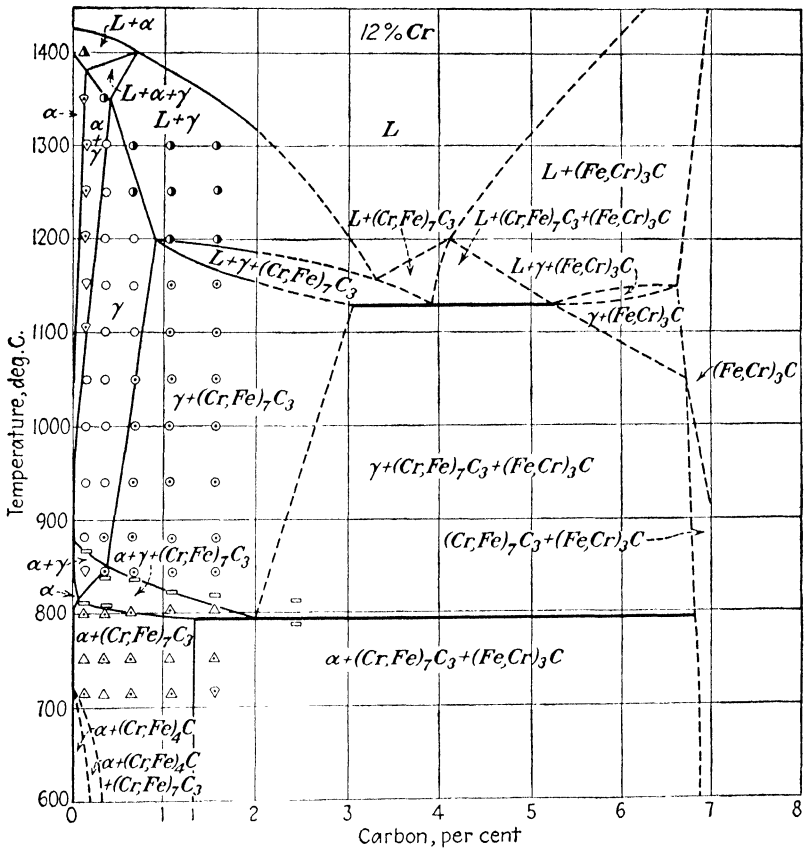


FIG. 44.—Section at 12 per cent chromium (47 6)

2. Alpha solid solution of the equilibrium $\alpha + (Cr,Fe)_7C_3 + (Cr,Fe)_4C$ is enriched in iron with declining temperature; the carbide $(Cr,Fe)_4C$ may appear in alloys containing as little as 10 per cent chromium.

3. Alloys containing 30 per cent chromium (Fig. 47) contain only alpha, $(Cr,Fe)_4C$, and $(Cr,Fe)_7C_3$ phases. Hardening by heat treatment is therefore impossible.

4. Precipitation of the compound FeCr in 40 to 60 per cent chromium alloys leads to great brittleness.

Figure 43, the 20°C. isothermic section, is of special interest in that it indicates the constitution of chromium steels and cast irons (in the equilibrium condition) at ordinary temperature. The condition of equilibrium is, of course, seldom if ever realized at low temperature, but even the limiting constitution is of value as a basis of comparison. To be noted also is the fact that this

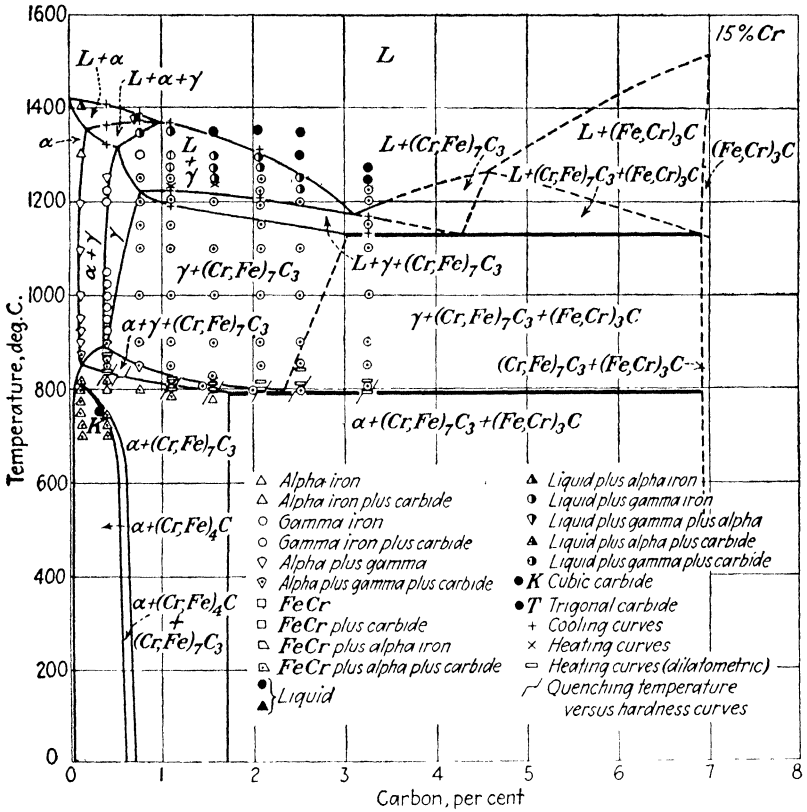


FIG. 45.— Section at 15 per cent chromium.(476)

section resembles the comparable section prepared by Westgren and his coworkers. The greater complexity of Fig. 43 arises from the inclusion of fields in which FeCr participates.

The low-carbon regions of the various sections yield further practical information. For example, it is shown that the solubility of carbon in the alpha phase of iron-rich alloys at temperatures immediately below the temperature of solidification

increases slightly with increased chromium content. It appears, to be specific, that the carbon solubility is increased to about 0.1 per cent at 12 per cent chromium, and about 0.2 per cent at 20 to 30 per cent chromium.

The gamma-phase region, as pictured by successive constant-chromium sections, becomes progressively smaller with increased

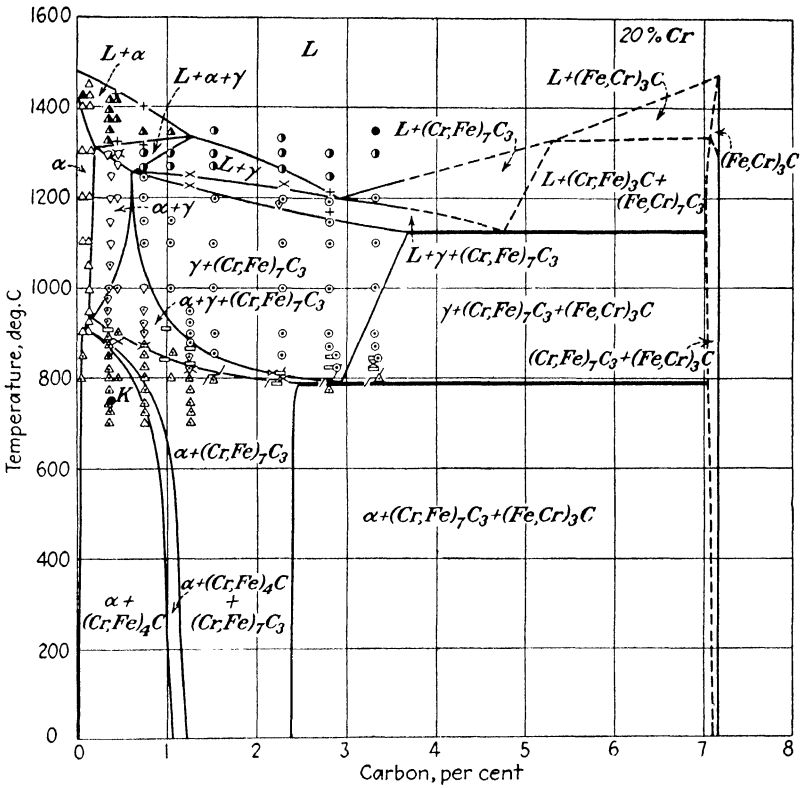


FIG. 46.—Section at 20 per cent chromium.[476]

chromium content; it disappears at about 20 per cent chromium. Further, the temperature limits of the region become narrower with increased chromium content. This means that successively higher temperatures must be used for heat-treatment operations that depend upon transformation to and from the gamma phase; this fact is the basis of the first practical conclusion on page 71. It follows also that, for maximum hardening by gamma-phase transformation, a carbon content must be chosen that lies in the

gamma-phase region for a given chromium content. It is clear that carbon in excess of the limit can participate only as free chromium carbide.

The maximum carbon content of gamma phase as shown by these sections is in good agreement with values reported by other investigators. Such agreement lends credence to the sections;

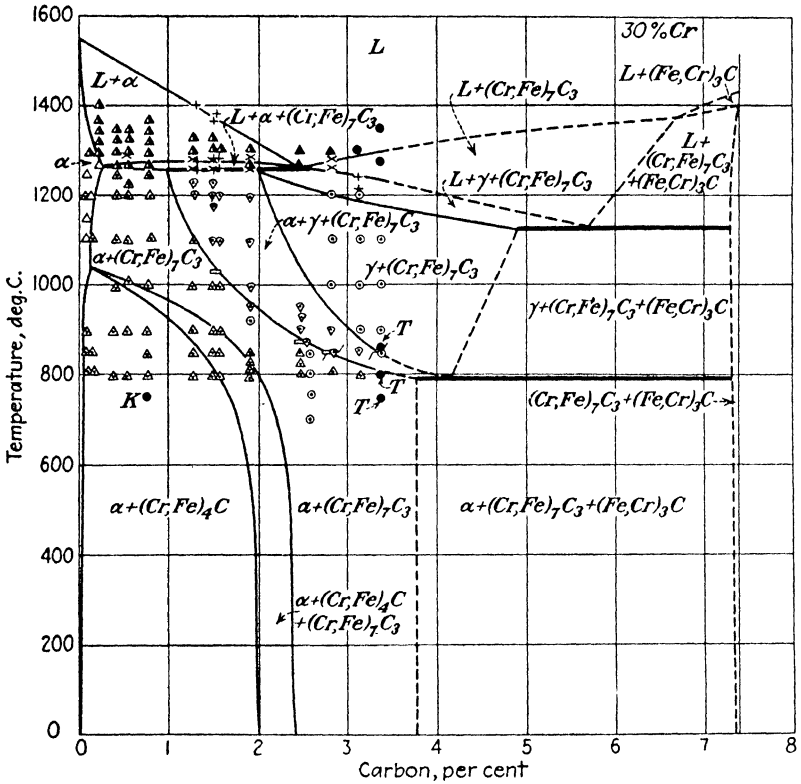


FIG. 47.—Section at 30 per cent chromium.[47b]

this, coupled with the fact that the diagrams were constructed with the underlying principles in view, on the whole, forces the conclusion that the status of the iron-chromium-carbon diagram is firmer than that of a number of ternary systems of which iron and carbon are two components. A few matters are indecisive; *e. g.*, perhaps five non-variant equilibria, all of the transition-plane type, exist. But this is not very important. It is likely that further work can only adjust, not discover.

C. AUTHORS' SUMMARY

1. The three contiguous binary diagrams of the iron-chromium-carbon diagram are all uncertain to an extent. This necessarily introduces uncertainty into the ternary diagram.

2. It is reasonably certain that the carbides of chromium are Cr_4C (or $Cr_{23}C_6$), Cr_7C_3, and Cr_3C_2. Carbide CrC has been

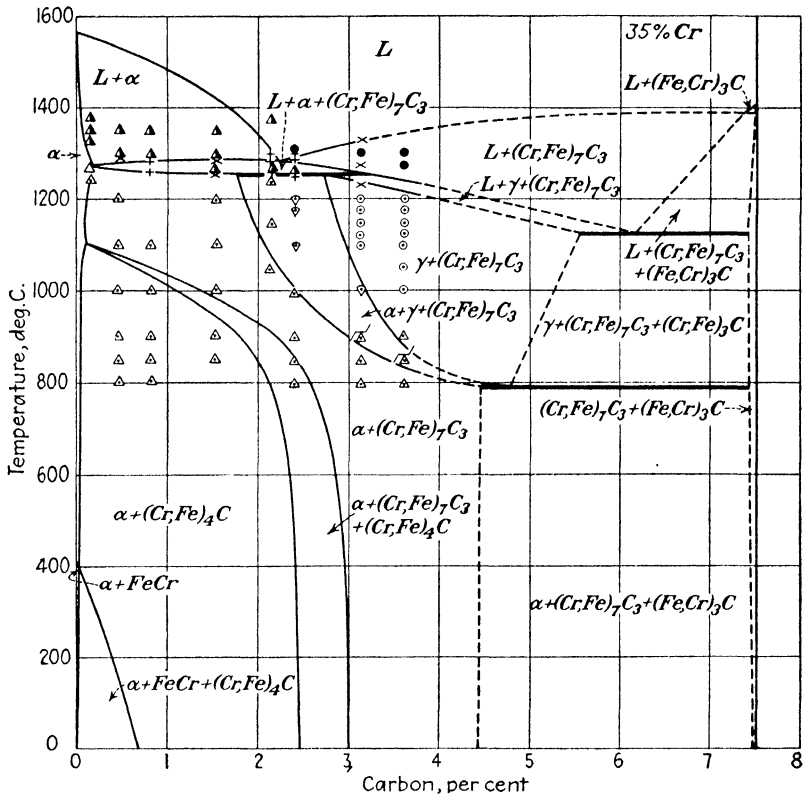


FIG. 48.—Section at 35 per cent chromium.[476]

proposed but not confirmed. For ternary alloys there is no trustworthy evidence of a double carbide; however, carbides of variable composition can be found because iron carbide Fe_3C dissolves chromium up to about 15 per cent, chromium carbide Cr_4C (or $Cr_{23}C_6$) dissolves iron up to about 25 per cent, Cr_7C_3 dissolves iron up to about 55 per cent, and Cr_3C_2 dissolves iron to the extent of a few per cent.

3. Experimental evidence indicates clearly that Cr_4C (or $Cr_{23}C_6$) appears as a result of peritectic transformation; this seems to be true also of Cr_7C_3, but the evidence is not conclusive. Cr_4C forms a eutectic with chromium at about 1485°C. and 3.7 per cent carbon. The form of the liquidus in the vicinity of Cr_3C_2 is unknown; one investigator postulated a temperature maximum.

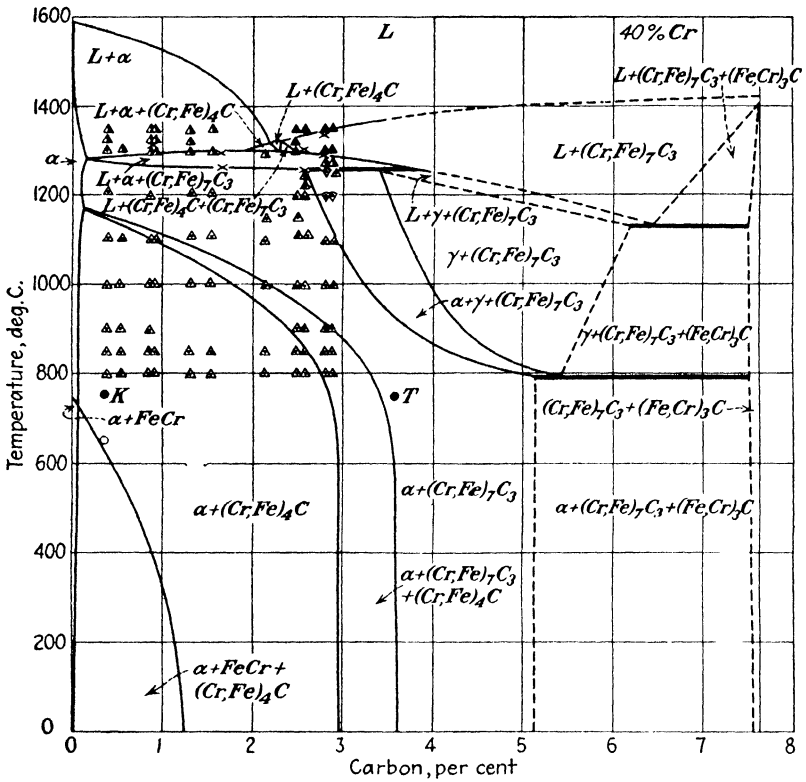


FIG. 49.—Section at 40 per cent chromium.[476]

4. The iron-chromium-carbon diagram is better established than some other ternary diagrams of which iron and carbon are two components.

The section Fe_3C-Cr_7C_3 of the ternary diagram seemingly behaves, in the solid state at least, as a quasi-binary system. This permits consideration of the partial system Fe-Fe_3C-Cr_7C_3-Cr. If the carbide Cr_7C_3 appears as a product of peritectic transformation, revision of the high-temperature portion of the

diagram in the vicinity of the Cr_7C_3 corner may be expected. However, assumption of this partial system permits construction of sections that satisfactorily account for the observed combinations of phases.

According to the best experimental results, four four-phase equilibria exist. Three of these are of the transition-plane type, and the other is of the eutectic type. In agreement with Austin's

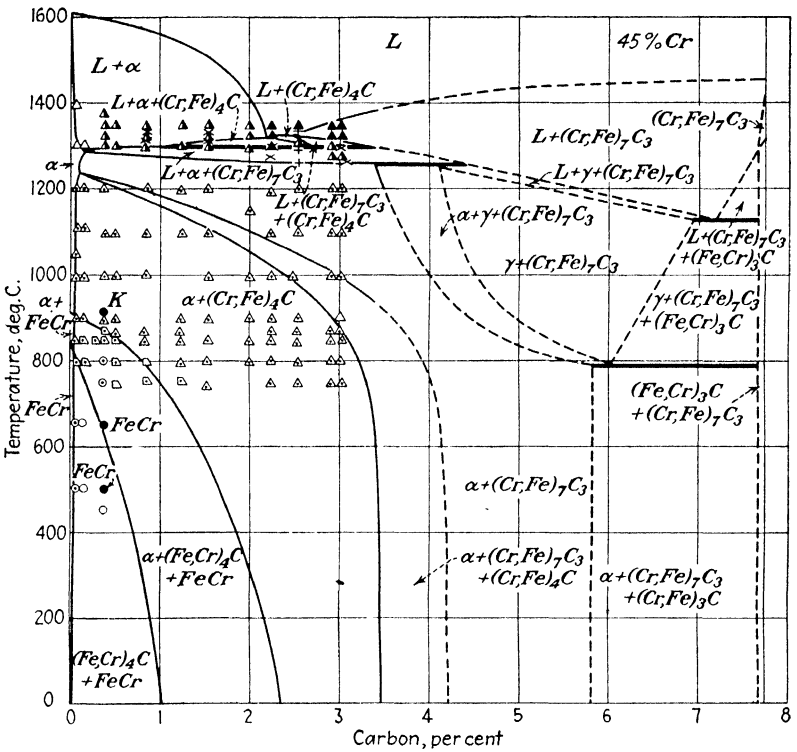


FIG. 50.—Section at 45 per cent chromium.(476)

conjecture (page 53), the ternary eutectic point lies close to the plane of the iron-carbon diagram. The non-variant equilibrium of greatest practical importance exists at 790°C. and involves the phases alpha, gamma, chromium carbide Cr_7C_3, and iron carbide Fe_3C. The coordinates of the alpha and gamma corners of the quadrangle are respectively 0.05 per cent carbon, 2.6 per cent chromium and 0.7 per cent carbon, 2 per cent chromium. Thus, the chromium carbide Cr_7C_3 is able to appear (this depends on the carbon content) in many chromium steels containing more

than 2 per cent chromium. The behavior of such steels in heat treatment is therefore different from that of carbon steels. This is best inferred from the appearance of the various sections of the diagram.

With less than 2 per cent chromium, the constitution of the alloys is not very different from that of iron-carbon alloys. The

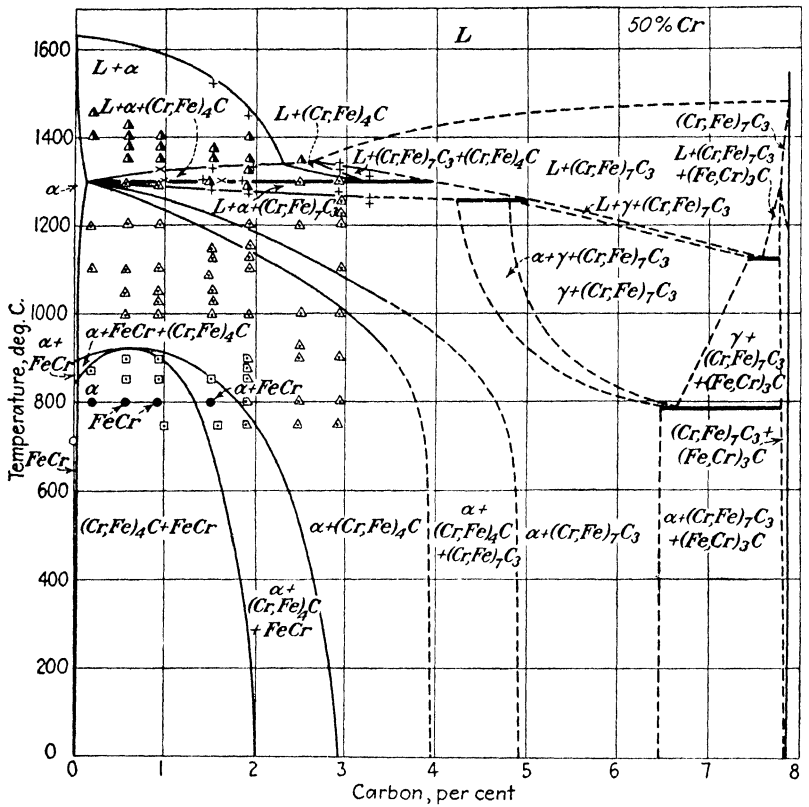


FIG. 51.—Section at 50 per cent chromium.(476)

only marked difference is that three-phase regions appear as areas rather than isothermic straight lines.

5. Of practical interest is the diminution of the gamma region with increasing chromium content; this means increasing restriction of the carbon content if alloys are to be transformed entirely to the gamma phase for heat treatment. Furthermore, the carbon content of the "eutectoid" is decreased by increasing the chromium content.

6. The compound of iron and chromium for which the formula FeCr seems probable does not participate in any of the high-temperature equilibria; this is fortunate, because otherwise the ternary diagram would be still more complicated.

7. To repeat, the general features of the partial system iron–iron carbide–chromium carbide–chromium are well known, and

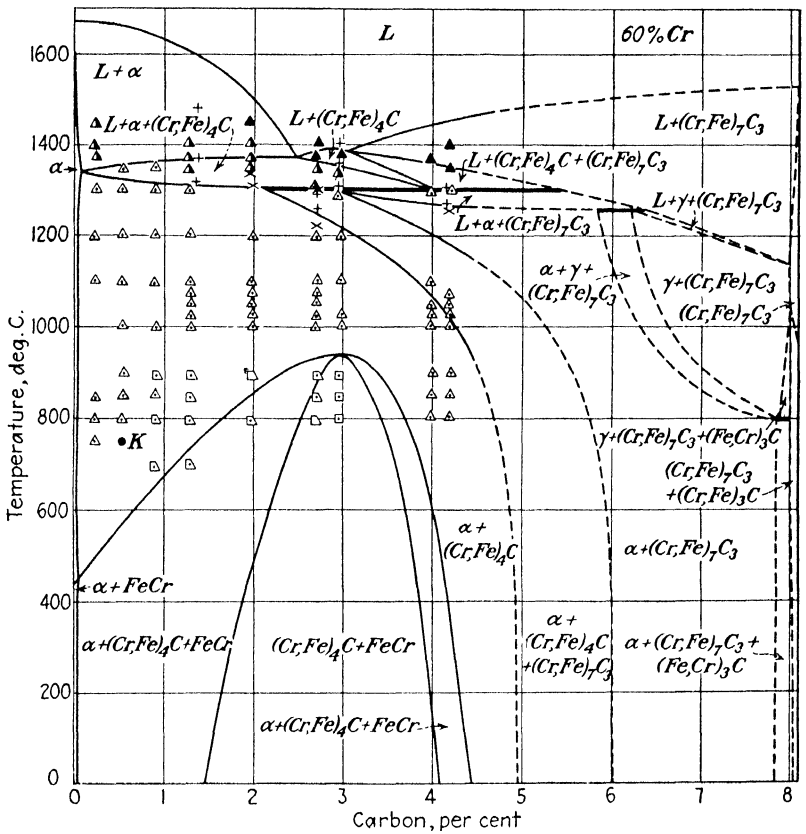


FIG. 52.—Section at 60 per cent chromium.[476]

specific details are better known than in many other ternary systems of which iron and carbon are two components, but some uncertainty remains. For practical purposes this uncertainty is unimportant. The sections given in Figs. 37 to 52 are adequate to interpret satisfactorily the behavior of all iron-chromium-carbon alloys now known.

CHAPTER IV

TRANSFORMATIONS IN CHROMIUM STEELS

Early Data on Transformations—Recent Data on Transformations—Authors' Summary

The preceding chapter on the iron-chromium-carbon system is concerned with alloys in the equilibrium condition. It is now widely appreciated that steels and other ferrous alloys as ordinarily used are seldom, if ever, in the equilibrium condition. However, equilibrium is approached to a greater or less degree in all heat treatments, even though reactions are arrested intentionally far from this state. Such heat treatment is made possible because time is a factor in the alpha $\rightleftharpoons$ gamma transformation and chromium has a marked influence on the rate of transformation at a given temperature.

In this chapter, iron-chromium-carbon alloys containing up to 35 per cent chromium with varying carbon are considered broadly. Together with Chapter III it should form the basis for an appreciation of the combined effects of chromium on transformation rates and on equilibrium in achieving a given result from heat treatment. Detailed discussion of transformation in more limited composition ranges is given in subsequent chapters. The range up to 3.5 per cent chromium comprises most of the chromium structural and engineering steels, and the work of Bain and Davenport, discussed in Chapter VI, showing the nature of the gamma-alpha transformation as a function of time as well as the effect of small percentages of chromium on the time factor, affords precise understanding of the phenomena in the lower chromium part of the range. The earlier work on transformations and critical points was carried out before the nature of the time factor was well understood, although even then its importance was appreciated. Accordingly, material summarized in this chapter has been treated as presented by the original investigators, and is chiefly on the changes that take place at

so-called "critical points" when chromium steels and related alloys are heated and cooled at ordinary rates.

A. EARLY DATA ON TRANSFORMATIONS

Osmond[17] in 1890 was the first to determine the effect of chromium on the "critical points" of steels. He concluded that, as chromium content is increased, the Ar_1 transformation temperature is raised, and that, if the rate of cooling is increased or the initial temperature raised, the critical points of high-chromium steels are lowered, thereby imparting the property of self-hardening.

34. Early Investigations (1905–1918) on Effect of Chromium on Transformations.—In 1905, Carpenter[34] determined the Ar_1 temperatures shown in Table 7. He concluded that since

TABLE 7.—Ar_1 TEMPERATURES OF CHROMIUM STEELS*

Composition, per cent		Cooled from, °C	Ar_1 temperature, °C.
C	Cr		
0.54	1 12	918	729
		1127	728
		1250	709
0 27	3 24	910	738
		1127	736
		1250	721
1 09	9 55	900	776
		1230	750

* Carpenter [34]

chromium tended to raise Ar_1 it hastened the carbide transformation and therefore could not be regarded as an element that imparted the property of self-hardening to steel. Carpenter also decided that the temperature from which the steel had been cooled had no great influence on the position of the Ar_1 point. Osmond[37] immediately took issue with these views and held to the opinion that, although chromium raised the critical point, it retarded the change of carbon from the hardening to the pearlitic condition.

McWilliam and Barnes[49] determined the critical temperatures of six samples of 2 per cent chromium steel containing various

TABLE 8.—CRITICAL TEMPERATURES OF 2 PER CENT CHROMIUM STEELS*

Carbon, per cent	Critical temperature, °C.					
	Ac_2	Ac_1	Ac_3	Ar_3	Ar_2	Ar_1
0.20	765	791	822?	785	765	732
0.25	759	789	810?	758	758	731
0 32	753	785	785	748	748	733
0.50	759	778	778	721	721	721
0.65	783	783	783	718	718	718
0.85	777	777	777	714	714	714

* McWilliam and Barnes.[49]

amounts of carbon. Their results are given in Table 8. Thermal analysis of the whole series indicated that the eutectoid composition lay somewhere between 0.65 and 0.85 per cent carbon.

TABLE 9.—CRITICAL POINTS OF CHROMIUM STEELS*

No.	Composition, per cent		Heating				Cooling			
			Rapid, 12° per min.		Slow, 3° per min		Rapid, 9° per min.		Slow, 3° per min.	
			Temperature, °C.				Temperature, °C.			
	Cr	C	Ac_2 max.	Ac_1 begins	Ac_2 max.	Ac_1 begins	$Ar_{3\,2}$ begins	Ar_1 max.	$Ar_{3.2}$ begins	Ar_1 max.
1	0 25	0 36	...	748	...	746	775	709	780	711
2	0 52	0.36	...	762	...	752	778	722	776	721
3	0.77	0.30	...	762	...	756	783	720	786	726
4	1 05	0 34	..	756	...	756	765	729	772	731
5	1 60	0.33	..	775	...	765	758	735	766	744
6	2 06	0.33	773	782	..	776	752	746	758	750
7	2.56	0 39	778	788	...	782	...	748	...	752
8	3 04	0.38	779	802	772	788	..	750	...	753
9	3.96	0.40	774	804	771	791	. .	747	.	753
10	5.03	0.46	780	820	778	810	...	754		768
11	5.85	0 57	778	812	774	810	...	766		772
12	4 16	0.32	773	820	774	818	...	746	.	763
13	5 41	0.25	785	829	776	813	...	734		755
14	6.42	0.26	776	826	777	821	.	750	.	769

* Moore.[50]

The microstructures showed that the steel with 0.65 per cent carbon was very near, or possibly slightly below, the eutectoid composition.

From Table 8 it may be noted that for these steels the Ac_2 point occurs at or below the Ac_1 point. This fact was discovered independently by Moore,[50] who noted that the carbide transformation points were raised by the presence of chromium and also verified Osmond's[17] view that Ar_1 was lowered by higher initial temperatures. He considered this latter effect to be greatest when the chromium content was high and the carbon content low. His values for the critical points of chromium steels are given in Table 9.

Murakami[75] stated that the Ac_1 and Ar_1 points of his chromium steels were raised as the chromium content was increased, and that the former became higher than the Ac_2 point for high-chromium steels.

35. Other Early Investigations (1920–1924).—Edwards, Sutton, and Oishi[84] determined the Ac_1 and Ar_1 points for a number of chromium steels. Table 10 shows their results. By plotting these data as isothermic lines, they were able to show that, as the chromium content was raised with the carbon content held constant, the A_1 change occurred at progressively higher temperatures until the ratio of carbon to chromium reached 1 to 10. A further increase of chromium caused a lowering of the temperature of the change. The same type of rise occurred when the carbon percentage was increased in a series of alloys with constant chromium content until the ratio was again 1 to 10, after which further increase of carbon caused a lowering of the transformation temperature. These facts led them to the conclusion that the chromium entered into chemical combination with the carbon in the alloys. Similar data were reported by Andrew, Rippon, Miller, and Wragg[80] for 1.6 per cent chromium steels.

Jones[98] determined the A_1 points and the effect of initial temperature on them for a series of steels containing 0.37 to 0.43 per cent carbon and 0.05 to 3.05 per cent chromium. These are given in Table 11.

Results obtained by Russell[101] on the A_2 and A_1 points of a number of chromium steels are given in Table 12. These data were obtained by means of differential and inverse-rate thermal curves. He confirmed Moore's[50] statement that the addition

of chromium progressively raises the Ac_1 point until it is higher than the Ac_2 point.

TABLE 10.—CRITICAL POINTS OF CHROMIUM STEELS*

Sample No.	Composition, per cent				Critical point, °C.	
	Cr	C	Si	Mn	Ac_1	Ar_1
1	1 03	0 28	0 03	0.28	771	737
2	1.12	0 56	0 20	0 55	769	728
3	1 96	0 33	0 05	0.14	797	743
4	2 08	0 87	0 18	0 19	792	757
5	2 09	1 00	0 17	0 29	790	748
6	2 11	1 26	0 18	0 20	774	745
7	2.10	1 81	0 12	0.37	760	730
8	2.94	0 38	0 08	0 32	805	762
9	3.92	1 09	0 27	0 18	795	757
10	4 02	0 30	0 15	0.18	817	764
11	4.19	0 95	0 32	0 10	801	767
12	4.69	0 70	0 34	0 43	811	769
13	4.72	0 11	0 14	0 09	830	739
14	4 93	1 46			790	752
15	5 07	1 07	0 19	0 21	803	767
16	6 15	0 63	0 07	0 17	822	784
17	6.16	0 97	0 31	0 15	825	785
18	6 18	0 37	0 32	0 24	833	768
19	6.20	0 70	0 14	0 18	824	785
20	7 05	0 80	0 14	0 22	826	787
21	8 08	0 43	0 43	0 25	833	774
22	8 12	1 02	0 37	0 11	829	794
23	9 15	0 90	0 18	0.14	833	783
24	10 39	0 37	0 50	0 19	835	764
25	10 42	1 14	0 46	0 08	836	800
26	12 08	0 38	0 58	0.24	830	762
27	12.60	0 28			827	750
28	15 06	0 21	0 12	.	826	750
29	18 31	1 98	0 08	0 31	822	738

* Edwards, Sutton, and Oishi [84]

Figure 53 shows the effect of chromium on the Ac_1, Ar_1, and Ac_2 points in steels averaging 0.75 per cent carbon and 0.45 per cent manganese, as determined by Scott.[129] Using inverse-rate curves, he found that Ac_1 was raised 11°C. and Ar_1 6°C. for each per cent chromium added up to 7 per cent, beyond which composition they remained stationary, and that Ac_2 was lowered

TABLE 11.—CRITICAL POINTS OF CHROMIUM STEELS*

Composition, per cent		Transformation on heating		Transformation on cooling					
					Temperature, °C., when initially cooled from				
C	Cr	Point	Temperature, °C	Point	1000°C	898°C.	811°C.	785°C	734°C
0 37	0 05	Ac_1	733	Ar_3 (start)	787	785	777		
		Ac_2	772	Ar_3 (max)	768	773	762		
		Ac_3 (end)	815	Ar_1	700	700	699	699	711
					Temperature, °C , when initially cooled from				
					1000°C	896°C	773°C		
0 37	0 75	Ac_1	752	Ar_3 (start)	772	772			
		Ac_3 (end)	802	Ar_3 (max)	764	764			
				Ar_1	714	718	725		
					Temperature, °C , when initially cooled from				
					1000°C	897°C	785°C		
0 38	1.43	$Ac_{1\,2\,3}$	770	Ar_3 (start)	760	767	758		
				Ar_3 (max.)	752	755	750		
				Ar_1	730	734	734		
					Temperature, °C , when initially cooled from				
					1000°C	896°C.	809°C	Held 3 hr at 809°C	
0 43	3 05	Ac_2	774	Ar_1	741	748	768	757	
		$Ac_{1\,3}$	791						

* Jones [98]

only by the higher percentages. Ac_2 crossed Ac_1 at 2.5 per cent chromium.

TABLE 12.—MAGNETIC AND CARBIDE CHANGE POINTS OF CHROMIUM STEELS*

Mark	Composition, per cent		Heating point, °C		Highest temperature attained, °C.	Cooling point, °C.	
	C	Cr	Ac_1	Ac_2		Ar_2	Ar_1
A	0 25	1 56	756†	770‡	942	781†, 767‡	729
			756	770	808	781†, 767‡	729
B	0 26	3 05	797	770	947	(?)	728
			797	770	843	770§	734
C	0 47	6.08	802	770	949 5		740 9 to 747 6
			804 5	770	819	. .	770
D	0 59	8 38	812 1	770	943		756 3 to 760 2
			811 6	770	826		764 1 to 767 9
E	0 64	12 2	818 1	767	941		746.5 to 749 3
			819 1	769	835		756 3 to 761 8
F	0 39	1 49	771	771	937	753†, 744 8‡	730 4
			772 2	772.2	813	761†, 744 8‡	728 5
G	0 46	3 02	789 4	770	951		733 4
			788 3	770	817	.	742 1
H	0 78	6 12	800 8	770	941		746 5 to 752
			800 2	770	813		764 1
I	0 77	9.03	812 †	770	943	.	756 to 761 3
			812 1	770	821		768 to 771 2
J	0 79	12 1	815 1	767	941	. .	755 3 to 757 5
			815 4	767	826	.	763 3 to 767 3
K	0 65	1.49	759	759	945	. .	719 3 to 729
			759	759	777	.	737 1
L	0 65	3 20	781 2	770	790 4		753 3
M	0 66	6 22	810	768	942		751 4 to 756 5
			809	769	848		769 to 772 5
N	0 87	8 85	813 2	770	937 4		765 5 to 773 4
				770	836 5	.	770 to 776 2
P	0 82	1 54	758 5	758.5	952		709 3 to 711
			758 5	758 5	792		727
Q	0 91	2 96	770	770	942		725 4 to 732 7
			770	770	821		741 to 742 7
R	0 86	5 70	795 1	770	939		743 9 to 748 9
			793 8	770	805		769
S	0 84	8 59			941		755 8 to 760 2
			811	771	845		756 8 to 760
T	1 08	11 36	814	767 4	940 5		761 6 to 765 3
			813 7	770	840	.	767 9 to 771 8
1686	0 50	13 22	819 7	745	953		711 5
			819 7	745	841		731
1687	0 65	13 34	818 1 to 816	750 3	948		725
				753	830		740
1688	0 44	9 0	812 7 to 808 9	764	950		729 3
			812 7 to 808 9	764	831		751 4
1689	0 50	8 21	814 3 to 811	767 4	950		737 1
			812 7 to 816 5		844		752 2 to 754 5
1690	0 44	5 46	809 to 807	770	947		727 1 to 731 5
			809 4 to 807 3	772	828		753 1
1091	0.85	10 15	818 7	774	952		759 1 to 769.8
			823 4	772	834		780 6
1092	0.88	15 02	823 5 to 822	756	945	.	742
					838		764

* Russell (101)
† Beginning of change.
‡ Maximum.
§ Approximate.

Aall(132) found that the A_1 temperature was raised 8.2°C., while the carbon content of the eutectoid was lowered about

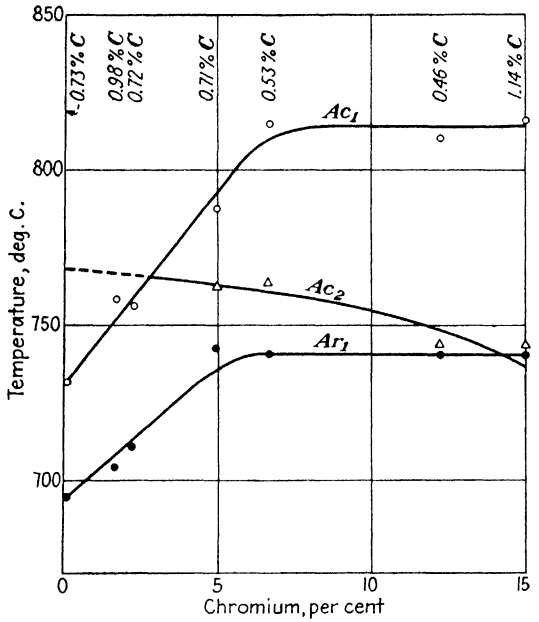


FIG. 53.—The effect of chromium on Ac_1, Ar_1, and Ac_2 in steels containing approximately 0.75 per cent carbon and 0.45 per cent manganese. (*Scott.*[129])

TABLE 13.—Ac_1 POINTS IN CHROMIUM STEELS*

Composition, per cent		Temperature of Ac_1, °C.	Composition, per cent		Temperature of Ac_1, °C.	Composition, per cent		Temperature of Ac_1, °C.
C	Cr		C	Cr		C	Cr	
0 05 to 0 06	Nil	730	0 04	11 3	810	0 80	22 0	835
0.05 to 0 06	0 4	735	0 05	11 6	810	0 11	16 5	820
0 05 to 0 06	0 6	740	0 05	12 1	810	0 15	16 9	820
0.05 to 0 06	1.0	745	0 16	13 9	810	0 56	22 1	890
0 05 to 0 06	1 4	760	0 15	16.9	820	0 13	19 8	940
0 05 to 0.06	2.0	775	0 56	21 0	890	0 74	24 7	940
0 05 to 0 06	2 6	785				0 77	26 3	1025
0 21	2 8	785				0 27	24 4	1230
0 21	5 8	805						
0.22	8.0	805						

* Kalling.[301]

0.066 per cent for each per cent chromium added. At the slow rate of cooling employed by Aall, the Ar_1 and Ac_1 points practically coincided. His steels contained from 0.15 to 0.64 per cent carbon and up to 12.9 per cent chromium. The carbon content apparently had little, if any, effect on the position of the A_1 point.

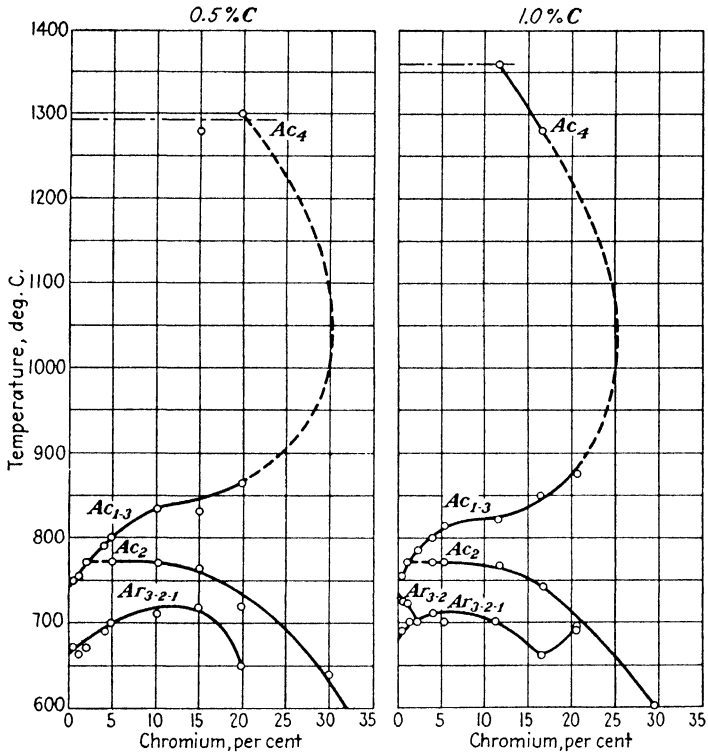


FIG. 54.—Critical points in chromium steels containing approximately 0.5 and 1 per cent carbon. (*Maurer and Nienhaus.*[225])

B. RECENT DATA ON TRANSFORMATIONS

36. Kalling's Investigation.—Kalling,[201] as the result of an examination of a number of steels containing up to 27 per cent chromium, concluded that the temperature at which the Ac_1 change occurred was independent of the carbon content for steels with fairly low chromium contents. When more than 15 or 16 per cent chromium was present in the steel, however, he found that the temperature of the Ac_1 change decreased with increase

in carbon content. In Table 13 it is seen that the Ac_1 change occurred at the same temperature in the two steels containing respectively 0.13 per cent carbon and 19.8 per cent chromium,

TABLE 14.—TRANSFORMATION POINTS (DILATOMETRIC) OF IRON-CHROMIUM-CARBON ALLOYS*

Specimen	Composition, per cent		Transformation points, °C.					
			$Ac_{1\,3}$		$Ar_{3.2}$		$Ar_{3\,2.1}$	
	C	Cr	Beginning	End	Beginning	End	Beginning	End
A	0 46	0 49	754	800	740	715	715†	695†
B	0 46	1.01	755	783	730	710	710†	690†
C	0 46	2 20	771	800			721	700
D	0 51	4.08	803	824			731	707
E	0 58	5 27	810	832			740	712
F	0.49	11 31	822	838			730	700
G	0 67	16 41	850	878			730‡	670‡
							370§	320§
H	0 72	20 45	860	910			810‡	770‡
							370§	320§
J	0 65	29 58						
K	0 87	0 54	752	772			692	671
L	1 02	0.97	758	780			699	678
M	1 03	1.98	768	792			702	683
N	1 20	4 18	774	796			708	691
O	1 02	4 85	788	811			721	703
R	1 20	10.13						
S	1 26	14 93	828	840			738	714
T	1 15	19 83	847	870			725‡	650‡
							370§	320§
V	1 19	29 91						
W	1 43	1 09	755	778			702	685
X	1 71	0 99	745	765			692	676
Y	1 51	4 03	772	793			710	693
Z	2 04	3 84	770	790			707	694

* Maurer and Nienhaus [226]
† Ar_1.
‡ Ar'.
§ Ar''.

and 0.74 per cent carbon and 24.7 per cent chromium. Kalling explained that this was due to the fact that the ferrite in both steels contained the same amount of chromium, since part of the

chromium is associated with the carbon as carbide, and an increase in the carbon content of the steel depletes the amount of chromium in the ferrite.

37. Investigation of Maurer and Nienhaus.—By means of thermal analysis Maurer and Nienhaus[225] determined the transformation points for a series of 22 iron-chromium-carbon alloys containing from 0.5 to 2 per cent carbon and 0.5 to 30 per cent chromium. The cooling rate used was 5 to 10°C. per min. The curves obtained for the effect of chromium on the critical points for alloys containing about 0.5 and 1 per cent carbon respectively are shown in Fig. 54.

TABLE 15.—COMPOSITION OF ALLOYS USED BY MURAKAMI, OKA, AND NISHIGORI[252]

Specimen No.	Composition, per cent		Specimen No.	Composition, per cent		Specimen No.	Composition, per cent	
	C	Cr		C	Cr		C	Cr
009	0 03	9 50	318	0.32	18 20	816	0 78	16 80
010	0 04	10 27	320	0 28	19 90	718	0 67	18 11
012	0 04	11 85	322	0.35	21 90	919	0 87	19 44
110	0 13	10 12	324	0 29	24 85	822	0 77	21 56
112	0 12	12 30				722	0 68	22 30
115	0.08	15 13	512	0.51	12 50			
116	0 19	16 30	514	0 51	14 10	823	0 86	23 06
118	0 10	18 10	516	0 57	16 45	725	0 66	24 90
121	0.10	21 20	518	0 54	17 80	827	0 79	26 80
124	0 10	24 08	621	0 58	20 85	1016	0 97	16 10
228	0 19	27 80	521	0 50	21 80	1017	0 95	17 20
230	0 20	30 20	524	0 54	23 60	1019	0 97	18 80
314	0 33	13 60	627	0 62	27 80	1021	0 98	21 50
315	0 37	15 60	814	0 82	14 00	1123	1 09	22 08
316	0.30	16 20						

A dilatometric determination of the critical ranges in the same series of alloys (Table 14) gave results comparable with those obtained by thermal analysis in spite of increased rate of cooling (10 to 15°C. per min.). By extrapolation it was found that the Ac_1 line intersected the Ac_2 line between 2 and 2.5 per cent chromium. The limit of the gamma field extended to 25 and 28 per cent chromium for the alloys containing 0.5 and 1 per cent carbon

respectively, as compared with their determination of 17 per cent chromium for a low-carbon alloy.

TABLE 16.—CRITICAL POINTS (DILATOMETRIC) OF IRON-CHROMIUM-CARBON ALLOYS*

Specimen No.	Temperature of Ac_1, °C.		Temperature of Ar_1, °C.		Specimen No.	Temperature of Ac_1, °C.		Temperature of Ar_1, °C.	
	Beginning	End	Beginning	End		Beginning	End	Beginning	End
009	807	863‡	815§	743	516†	841	899	836	747
010	812	845‡	807§	762	518†	852		.	728
012	816	882‡	798§	759	621†	934			800
110	809	863‡	825§	786	521†				
112	830	920‡	790§	740	524†				
115	837	925	840	767	627†				
116	850		.	822	814	809	823	780	759
118					816	828	846	792	770
121					718†	854	982	872	721
124					919†	853	902	776	700
228					822†	887			
230					722†				
314	819	904‡	810§	790	823	943		.	868
315†	842	910‡	825§	782	725†				
316†	849	950‡	850§	784	827†	1021		.	977
318†	867	895	800	762	1016†	812	817	761	747
320					1017	821	828	770	751
322†	963			743	1019	840	861	799	773
324†					1021†	862			
512†	813	840	771	757	1123†	870			792
514†	816	844	772	722					

* Murakami, Oka, and Nishigori [252]

† Specimens heated for measurement without previous annealing

‡ Ac_3

§ Ar_3.

38. Investigations of Murakami and Associates.—Murakami and Fujii[298] studied the effect of carbon upon the critical points of eight steels containing about 12 per cent chromium, using thermal dilatation and magnetization methods. They found that as the carbon content increased from 0.09 to 2.04 per cent the A_1 transformation temperature decreased slightly, while the A_2 transformation temperature increased slightly.

Murakami, Oka, and Nishigori,[252] whose general diagram for the system has already been given (Fig. 28, page 57), determined the transformation points of a number of chromium steels. Critical points determined dilatometrically on alloys whose composition is noted in Table 15 are given in Table 16. Their measurements of thermal dilatation resulted in the following conclusions:

1. When the carbon content was held constant and the chromium content was increased, the magnitudes of the A_3 and A_1 transformations gradually decreased until they could no longer be detected. The transformation temperature rose gradually at first and then more rapidly as the chromium content increased.

2. When the chromium content was kept constant, the A_1 transformation increased in magnitude, and its initial temperature on heating dropped as the carbon content increased.

39. Other Recent Investigations.—Valenta[304] determined the critical points of a number of high-chromium high-carbon alloys; the analyses are given in Table 17 and the data on critical points in Table 18. He also determined the temperature at which the alloys entered the gamma phase on heating. As Valenta's alloys contained up to about 1 per cent silicon, his critical-point data cannot be considered accurate for the iron-chromium-carbon system. His results are, nevertheless, reproduced here in view of the usual presence of silicon in ordinary commercial alloys.

An especially valuable set of data on transformation temperatures of iron-carbon-chromium alloys was reported by Tofaute, Sponheuer, and Bennek.[439] This is reproduced in Table 19.

40. Structural Classification of Chromium Steels.—The foregoing data on critical ranges were obtained either by thermal analysis or by dilatometry. For completeness, microstructures of air-cooled 1-in. section bars are classified graphically in Fig. 55. A diagram of this sort was first proposed by Guillet,[39] although Osmond[19] had listed the microstructures to be found as early as 1892. It is clear that a structural diagram such as Fig. 55 is valid only for the condition of heat treatment specified, because all constituents indicated are reaction products.

C. AUTHORS' SUMMARY

1. Data on transformation temperatures of chromium steels for ordinary rates of heating and cooling are summarized in this

TABLE 17.—COMPOSITION OF ALLOYS USED BY VALENTA[304]

Alloy No.	Composition, per cent				Alloy No.	Composition, per cent			
	C	Cr	Si	Other elements		C	Cr	Si	Other elements
1	3 16	30 49	0 40	0 36 Mn 0 024 P 0 044 S	69	0.70	15.70	0 31	
					70	0 40	24 12	0 69	
					71	1 31	23.04	0.65	
3	2 12	27 0	0 55		72	0 36	28 16	0 66	
5	2 91	20 82	0 98		73	0 74	22.09	0 61	
7	0 82	28 69	0 75		74	0 96	22 52	0 73	
9	1 95	29 14	0 82		75	1 28	21 70	0 87	
11	1 20	26 31	0 54		76	0 77	18.38	0 66	
13	1.60	35 35	1 03		77	1 07	18 38	0 71	
15	0 87	36 85	0 52		78	0 73	16 50	0 54	
17	2 87	36 85	0 52		79	0 99	16 27	0 52	
19	2 88	28 10	0 54		80	1 25	16 50	0 61	
21	1 10	19 69	0 38		81	0 57	14 78	0 56	
23	1 88	21 84	0 47		82	0 73	14 08	0 56	
25	1 33	15 40	0 26		83	1 07	14 78	0 59	
27	2 78	15 20	0 26		84	1 80	34 25	0 94	
29	1 46	31 53	0 56		85	0 63	25 22	0 35	
35	0 23	9 02	0 38		86	0 92	25 81	0 52	
36	0 31	8 98	0 33		87	1 61	25 42	0 49	
37	0 22	9 29	0 35		88	1 96	25 55	0 54	
39	2 20	10 89	0 35		89	2 50	25 62	0 66	
41	1 99	19 94	0 66		105	2 00	33 15	0 94	
43	2 86	24 41	0 49		106	0 76	19 03	0 94	
55	2 57	32 03	0 80		107	0 56	16 44	0 62	
56	0 50	34 82	0 42		108	0 56	14 23	0 53	
57	1 47	29 55	0 45		1*S*	3 31	33 33	0 81	0 52 Mn
58	2 97	10 69	0 19		2*S*	2 56	21 75	1 06	0 28 Mn
59	3 60	10 28	0 52						0 054 P
60	3 29	14 86	0 66						0 017 S
61	3 31	19 74	0 66		3*S*	2 09	24 06	0 63	0 092 P
62	3 51	24.23	0 73						0 022 S
63	2 18	14 76	0 31		4*S*	1 35	13 98	0 45	0 069 P
64	1 25	4 78	0 68						0 035 S
65	1 84	4 76	1 08		5*S*	1 29	10 75	1 03	0 086 P
66	2.92	4 72	0 66						0 028 S
67	0.18	15 12	0 25		8*S*	2 13	22 89	0 42	
68	0.15	19 05	0 21						

TABLE 18.—CRITICAL POINTS AND TEMPERATURES OF ENTRANCE INTO GAMMA PHASE ON HEATING FOR IRON-CHROMIUM-CARBON ALLOYS*

Alloy No.	Curve No.	Entrance into gamma phase on heating, °C.	Time for temperature rise from 20 to 1000°C., min.	Time for 100°C. temperature rise in critical range, min.	Condition	Critical points on cooling, °C.				Time for temperature drop from 1000 to 20°C., min.	Time for 100°C. temperature drop in critical range, min.
						Ar	*Ar'*	*Ar''*	(?)		
1	139	830 to 860	167	30	Annealed	770 to 740				222	22
	175	820 to 870	145	24	After curve No 139			205 to 20		191	
3	160	840 to 890	152	26	Annealed		750 to 660	400 to 200		216	10, 145
	161	840 to 890	113	19	After curve No. 160			220 to 20		11	
5	166	830 to 860	173	30	Annealed	780 to 750				224	31
	167	830 to 860	140	25	After curve No. 166			190 to 20		121	
7	152		157		Annealed			. .		230	
	153		108		After curve No. 152			.	500 to 300	14	
	154		129		After curve No. 153				400 to 200	12	
9	128	850 to 920	164	29	Annealed	795 to 720				201	23
	130	850 to 930	96	11	After curve No 128			200 to 20		16	
	131	870 to 930	112	20	After curve No. 130	790 to 725				192	32
11	158	870 to 930	144	20	Annealed	920 to 840				225	16
	159	870 to 930	141	26	After curve No. 158			220 to 200		14	
13	170		163		Annealed					217	
	171		140		After curve No 170				400, 200	9	
15	206		184		Annealed					247	
	207		148		After curve No 206				300, 200	12	
17	180	910 to 940	167		Annealed	840 to 780				243	23
	181	910 to 940	129		After curve No 180			170 to 20		15	
19	204	840 to 880	109	28	Annealed	770 to 650				207	10
	205	830 to 880	145	17	After curve No. 204			100 to 20		11	
21	190	830 to 870	174	20	Annealed	(?)	(?)	(?)	(?)	249	
	191	820 to 860	111	14	After curve No. 190			100 to 20		12	
23	176	825 to 875	146	20	Annealed	(?)	(?)	(?)	(?)	82	
	177	820 to 860	174	20	After curve No 176	760 to 705				225	34
	178	820 to 860	149	21	After curve No 177			180 to 20		14	
25	182	810 to 860	170	26	Annealed	765 to 705				232	32
	183	810 to 865	149	26	After curve No. 182			170 to 20		16	
27	255	750 to 800	163	26	Annealed	740 to 690				261	22
	257	760 to 800	159	20	After curve No 255			120 to 20		14	
29	259	<1000	180	33	Annealed	>1000				295	21
	261	<1000	149	19	After curve No 259	1000				297	21
	263	<1000	118	22	After curve No 261			180 to 20		13	
	265	<1000	138	24	After curve No 263			180 to 20		14	
	363	>940	154	20	After curve No 265	>940				185	21
	365	>940	134	14	After curve No 363			200 to 20		10	
35	270	800 to 840	119	26	Annealed		(?)	(?)		264	
	272	800 to 850	101	18	After curve No 270			290 to 70		151	
36	282	810 to 850	87	22	Annealed			300 to 70		14	
39	330	800 to 850	154	16	Annealed	770 to 720				111	20
	331	800 to 850	113	17	After curve No. 330			180 to 20		13	
41	274	830 to 875	124	21	Annealed	750 to 670				215	21
	287	830 to 875	102	15	After curve No. 274			200 to 20		10	
43	290	(?)	116		Annealed			190 to 20		11	
55	306	857 to 920	140	16	Annealed	800 to 720				232	19
56	367		141		Annealed					107	
	369		125		After curve No. 367					15	
57	302	<1000	135	14	Annealed	>1000				229	15
	304	<1000	119	18	After curve No. 302				180 to 20	16	
58	297	<900	158	18	Annealed	>880				222	16
	299	<900	135	13	After curve No. 297	880 to 820				218	20
	300	<900	108	9	After curve No 299			190 to 20		15	
	379	>900	155	17	After curve No. 300	<870				116	19
	381	>900	126	12	After curve No. 379			200 to 20		11	
60	278	770 to 850	128	17	Annealed			100 to 20		14	
	303	760 to 840	132	17	After curve No 278	770 to 700				112	20
	304	(?)	131		After curve No. 303	780 to 700				180	22

TABLE 18.—CRITICAL POINTS AND TEMPERATURES OF ENTRANCE INTO GAMMA PHASE ON HEATING FOR IRON-CHROMIUM-CARBON ALLOYS.*—(*Continued*)

Alloy No.	Curve No.	Entrance into gamma phase on heating, °C.	Time for temperature rise from 20 to 1000°C., min.	Time for 100°C temperature rise in critical range, min	Condition	Critical points on cooling, °C.				Time for temperature drop from 1000 to 20°C., min.	Time for 100°C. temperature drop in critical range, min.
						Ar	*Ar'*	*Ar''*	(?)		
61	345	820 to 850	142	21	Annealed	760 to 730				159	18
	347	820 to 850	112	12	After curve No. 345			100 to 20		17	
62	354	840 to 860	126	20	Annealed	780 to 750				138	30
	356	840 to 860	124	20	After curve No. 354	(?)				15	
63	349	800 to 820	136	19	Annealed	740 to 710				157	13
	351	800 to 820	93	18	After curve No. 349			150 to 20		16	
64	388	755 to 790	123	19	Annealed	715 to 700				183	16
	390	755 to 795	92	21	After curve No 388			180 to 20		16	
65	383	770 to 820	119	22	Annealed	750 to 720				154	19
	384	780 to 820	135	15	After curve No. 383		600 to 500	170 to 20		15	
66	382	760 to 790	122	20	Annealed	745 to 710				220	21
	386	760 to 790	90	10	After curve No 382		600 to 500	180 to 20		15	
72	375	. .	153		Annealed					92	
	377	. .	139		After curve No. 375					16	
73	535	(?)	144		Annealed	(?)				68	
	541	(?)	126		After curve No. 535	(?)				173	
	543	(?)	114		After curve No 541			210 to 20		16	
74	536	>880	153	21	Annealed	<900				193	20
	538	>880	153	26	After curve No. 536	900 to 800				145	18
	539	>880	125	14	After curve No. 538		. .	230 to 20		15	
75	521	850 to 935	137	15	Annealed	<770	. .			70	10
76	544	>810	112	13	Second heating		.	180 to 20		16	
78	546	810 to 930	108	16	Annealed			240 to 20		16	
79	504	830 to 880	143	16	Annealed	730 to 660				135	15
	506	830 to 880	118	18	After curve No 504			100 to 20		15	
80	508	815 to 880	105	15	Annealed			130 to 20		15	
	511	800 to 880	140	20	After curve No 508	790 to 640				110	21
	517	800 to 880	101	16	After curve No 511			250 to 20		15	
81	500	830 to 900	135	18	Annealed	(?)				95	
	502	830 to 900	110	12	After curve No. 500			180 to 20		15	
82	496	820 to 900	145	21	Annealed	780 to 700				110	20
	498	830 to 890	100	14	After curve No 496			450 to 20		16	
84	455	>955	183	19	Annealed	<855				175	22
	457	920 to 990	98	5	After curve No 455	(?)	(?)	(?)		16	
85	555	(?)	150		Annealed					115	
	557	(?)	135		After curve No 555					16	
86	426	(?)	125		Annealed	(?)				128	
	427	(?)	105		After curve No 426			230 to 20		17	
87	407	815 to 900	116	18	Annealed	725 to 640				110	15
	408	810 to 900	110	22	After curve No. 407			230 to 20		11	
88	451	880 to 890	144	20	Annealed	760 to 670				157	18
	453	820 to 890	112	12	After curve No 451			{220 to 160} {160 to 20}		15	
	523	810 to 880	124	16	After curve No 453			210 to 20		16	
	525	800 to 880	129	19	After curve No. 523	750 to 670				185	18
	529	810 to 870	103	13	After curve No 525			270 to 20		16	
89	441	840 to 930	94	11	Second heating			100 to 20		14	
105	547	920 to 960	155	22	Annealed	<800				155	15
	549	920 to 960	150	14	After curve No. 547			(?)		16	
	566	900 to 960	153	18	After curve No. 549	<800				142	20
	568	900 to 1000	140	13	After curve No. 566			180 to 20		15	
	578	910 to 1000	160	19	After curve No. 568	800 to 700				150	16
	579	>910	118	12	After curve No. 578			100 to 20		16	
106	581	>880	142	20	Annealed	850 to 700				211	22
	582	880 to 970	120	17	After curve No 581			200 to 20		17	
108	567	800 to 920	152	20	Annealed	(?)				143	
	569	800 to 920	129	16	After curve No. 567			200 to 20		16	

* Valenta.(804)

chapter. They pertain to alloys containing up to 35 per cent chromium and lend supporting evidence to the equilibrium diagram.

TABLE 19.—TRANSFORMATIONS IN CHROMIUM STEELS*

Steel No.	Composition, per cent				Transformation temperature, °C., from		
	C	Si	Mn	Cr	Hardness curve	Thermal-analysis curve	Dilatometric curve
1601	0 10	0 36	0 43	1 62	750 to 880	770 to 860	750 to 852
1604	0.41	0 46	0 50	1 57	725 to 800	760 to 780	751 to 781
1607	0 70	0 47	0 53	1 65	725 to 750	760 to 770	749 to 771
1610	1.02	0.44	0.50	1 64	725 to 750	740 to 755	743 to 764
1615	1 51	0 42	0 59	1.59	725 to 750	738 to 755	742 to 756
3001	0 09	0 42	0 39	3 01	800 to 850	815 to 835	795 to 835
3004	0 39	0.52	0 48	3 11	800 to 850	805 to 825	788 to 811
3007	0 72	0 53	0 52	3.18	750 to 850	790 to 820	770 to 800
3010	1.00	0 55	0 55	3 12	750 to 800	775 to 805	763 to 795
5001	0 10	0 37	0.37	4 86	800 to 850	815 to 820	805 to 823
5004	0 39	0 48	0 49	5 00	800 to 850	815 to 815	798 to 813
5007	0 72	0 48	0 55	5 10	750 to 850	800 to 805	785 to 799
5010	1 00	0 56	0 53	4 94	750 to 800	780 to 795	792 to 800
8001	0 12	0.55	0 47	8 00	800 to 850	815 to 840	802 to 820
8004	0 40	0.77	0 54	8 20	800 to 850	790 to 805	804 to 823
8007	0 67	0.56	0'52	8 10	800 to 850	795 to 800	796 to 815
8010	0 97	0 50	0.58	8.30	750 to 850	805 to 825	796 to 808
12001	0 14	0.58	0 33	11.80	830 to 880	825 to 860	818 to 866
12004	0 41	0 58	0 47	11 70	800 to 850	840 to 855	815 to 841
12007	0 69	0 56	0 48	12 30	800 to 850	840 to 845	801 to 824
12010	1 08	0 58	0 58	12 00	800 to 850	830 to 840	797 to 815
12015	1 58	0 59	0 60	11 90	750 to 800	830 to 840	795 to 812
12025	2 44			12 00		793 to 815	780 to 800

* Tofaute, Sponheuer, and Bennek [419]

2. In view of the complexity of the transformation when more than 2 per cent chromium is present, identification of transformations is difficult. That such complexity exists may be concluded from the sections of the iron-chromium-carbon diagram

given in Chapter III. The concepts involved in these sections were not known to the early investigators, and it is not strange that their identification of transformations was often incorrect.

3. Chromium increases the temperature at which the A_1 transformation takes place on heating, and this increase in temperature seems to be relatively independent of the rate of heating and approaches the equilibrium temperature for normal rates.

4. For the equilibrium condition, the alpha–gamma–iron carbide equilibrium, often called the A_1 point, proceeds to higher temperatures as chromium content is increased. The limits are about 720°C. at the iron-carbon plane and about 790°C. at the

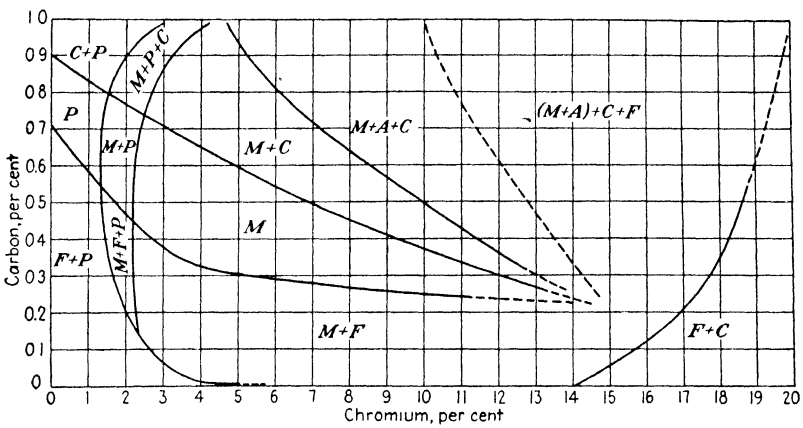


FIG. 55.—Structural diagram of iron-carbon-chromium alloys, air cooled in 1-in. sections. F = ferrite P = pearlite. M = martensite. A = austenite. C = carbide. (*Union Carbide and Carbon Research Laboratories, Inc.*)

non-variant equilibrium. Evidence of the alpha-gamma-carbide region may be obtained beyond these limits if rates of heating and cooling are appreciable. Strictly speaking, there is no eutectoid point for chromium steels (or any alloy steels); the line of twofold saturation originating in the iron-carbon eutectoid (gamma $\rightleftharpoons$ alpha + carbide), however, proceeds in the direction of lower carbon content and higher temperature as chromium content is increased. Since the section of this line at a given chromium content is a point, the practice of speaking of the "eutectoid point" of an alloy steel is understandable though inaccurate.

5. The effect of chromium of increasing the sluggishness of the transformation on cooling, that is, increasing the time factor in the gamma-alpha transformation, is shown by the data. This

phenomenon in the very low chromium ranges is well explained by the *S*-curve studies of Bain and Davenport, but much remains to be done to afford a clear understanding and quantitative picture of the effect of larger concentrations of chromium on the time factor.

6. The tabulated data in this chapter are useful in showing the temperatures at which transformations take place under the conditions of the original measurements. They may or may not be directly applicable to the field of practical heat treatment.

7. A structural diagram is given which shows the microstructures to be found in iron-chromium-carbon alloys for specified conditions of heat treatment. The diagram is not necessarily valid for other conditions.

8. The data and diagrams in this chapter present a survey of the general effects of chromium on the transformation temperatures, and detailed discussion of the more specific effects of specific chromium concentrations will be found in the subsequent chapters.

CHAPTER V

GENERAL EFFECTS OF CHROMIUM IN IRON AND STEEL

Classification of Chromium Irons and Steels—General Effects of Chromium in Manufacture and Heat Treatment—General Effects of Chromium on Physical and Chemical Properties

In the introduction of Chapter I, this monograph was likened to an atlas in which the field of knowledge of chromium is charted. In any atlas, detailed maps of the various fields which constitute the entire terrain, as well as a general map of the terrain as a whole, are considered essential; so, too, the present chapter giving a bird's-eye view of the entire subject is included in this monograph. It is intended to sketch the entire subject in such a way that the relationships of the specifically limited chapters to each other and to the whole can be more readily appreciated. With intent, detail is omitted, being included in the appropriate specific chapters. This chapter is not intended for the reader who is thoroughly familiar with the entire field and wishes to use this monograph primarily as a reference work, but it should be read carefully by those who have not had this advantage, in order that they may acquire the background for a better understanding of the specific phases of the subjects later covered in the book.

It has been suggested that this chapter might well have been the first in the book, but after serious consideration it was decided to have it follow the discussion of the historical background and the equilibrium diagrams, just as in a geography the map of the world follows chapters on cosmology and geology and precedes the charts showing individual continents and countries. It is hoped that these remarks are sufficient to justify the existence of this chapter in a monograph whose function is considered to be primarily that of a reference book.

The constitutional relationships of carbon, chromium, and iron have been discussed from the basis of the phase rule, equilibrium diagram, and microstructure in the foregoing chapters. The

various relationships thus shown, together with the effect of chromium on the rate of solution and transformation, are reflected in the mode of manufacture, in the response to heat treatment, and in the physical and chemical properties of the material. Thus, for example, experience shows that the higher the chromium and the lower the carbon, the more skill is required to prepare a satisfactory, clean, deoxidized melt. The higher the carbon and the higher the chromium, the more difficult it is to forge the material. The higher the chromium and the lower the carbon, the more corrosion-resistant is the material and the less susceptible is it to heat treatment. Again, increasing the chromium and the carbon, together with a suitable heat treatment, results in increased tensile and yield strengths and increased hardness. It will be seen readily that by proper selection of the chromium and carbon contents steels may be chosen which vary widely in the ease or difficulty of manufacture and in their chemical and physical properties.

A. CLASSIFICATION OF CHROMIUM IRONS AND STEELS

Broadly speaking, the chromium steels may be divided into five classes based upon chromium content. These are: (1) structural and engineering steels and cast irons containing up to 3.5 per cent chromium; (2) special-purpose steels containing 3.5 to 10 per cent chromium; (3) corrosion- and oxidation-resisting steels and special cast irons containing 10 to 16 per cent chromium; and two classes of higher chromium corrosion- and oxidation-resisting engineering steels, (4) those containing 16 to 22 per cent chromium and (5) those containing more than 22 per cent chromium. For the purpose of logical presentation, the subject matter in the following chapters is so divided.

41. Structural and Engineering Steels Containing up to 3.5 Per Cent Chromium.—An alloy of iron and carbon containing up to 3.5 per cent chromium may be classed as an engineering steel, a tool steel, or a cast iron, depending upon the carbon content. Such steels and cast irons owe their value to the improved physical properties and improved susceptibility to various types of heat treatment. Except in certain specific modifications, the corrosion resistance of these steels is not sufficiently greater than that of plain carbon steel to be of importance. In this category are to be found automotive steels,

high-strength structural steels, certain die steels, ball- and roller-bearing steels, and certain rail steels and spring steels. These steels—frequently containing one or more other alloying elements, but sometimes without modifying alloys—make up a large proportion of the total tonnage of wrought alloy steels produced. Alloy-steel castings with high strength and ductility are also included in this group. Again, in this category are found engineering types of alloy cast iron for such parts as Diesel-engine cylinders, crankshafts, and other applications where a pearlitic high-strength cast iron is desired. A large part of the data summarized in this book was obtained on steels and cast irons of this type.

42. Steels Containing 3.5 to 10 Per Cent Chromium.—The next category includes chromium above 3.5 per cent to approximately 10 per cent. Here, increased corrosion or oxidation resistance imparted by the chromium to ordinary irons or steels is generally of marked importance. Although these steels are certainly not to be considered stainless, the rate of corrosion is decreased to a sufficient degree to give them economic usefulness, and the higher the chromium the greater the degree of corrosion resistance. Most of the steels in this category are in the low-carbon class, and their excellent physical properties, together with moderate corrosion resistance, result in wide application in the petroleum and chemical industries. High-carbon steels in this category are restricted almost entirely to the magnet steels and certain valve steels, although high-speed steels may also be included. Castings with medium carbon and 3.5 to 10 per cent chromium are also included in this classification. These materials are discussed in detail in Chapters X, XI, and XIII.

43. Corrosion- and Oxidation-resisting Irons and Steels Containing 10 to 16 Per Cent Chromium.—The next broad group comprises the steels containing 10 to 16 per cent chromium; these are the steels in which resistance to atmospheric corrosion—although varying over wide limits—is so great that they are commonly classified as "stainless." This category illustrates perhaps better than any other the wide variation of properties resulting from various chromium and carbon contents. A gradual change from high corrosion resistance to high wear resistance occurs as the carbon increases; a splendid combination of both is well illustrated by the cutlery steels. As the chromium

content increases beyond 10 per cent the corrosion resistance increases rapidly, so that at approximately 12.5 per cent chromium it is such that the polished surface of a well-made low-carbon steel does not tarnish in ordinary atmospheres and has, at room temperature, a high degree of resistance to nitric acid. Moreover, these steels, with 0.10 per cent carbon, far surpass the carbon and low-alloy engineering steels in ductility at a tensile strength of 100,000 lb. per sq. in., at which strength level they are commonly used for engineering purposes. The amount of chromium necessary to impart a given degree of corrosion resistance depends on the carbon content. Broadly speaking, the 12.5 per cent chromium steel with 0.10 per cent carbon is decidedly corrosion resistant, whereas the 14 per cent chromium steel with 2.5 per cent carbon is attacked very readily. Oxidation resistance also increases rapidly with the increase of chromium, particularly in the vicinity of 12 per cent chromium; the strength at high temperatures also increases rapidly in this chromium range. Many extremely useful products are found in this category; namely:

Corrosion-resistant iron with 12.5 per cent chromium and up to 0.10 or 0.12 per cent carbon.
Stainless cutlery steels with 13 or 16 per cent chromium and 0.20 to 0.60 per cent carbon.
Special tool steels with 12 to 16 per cent chromium and 1 per cent carbon.
Special die steels with 12 per cent chromium and 2 per cent carbon.

Again, cast irons with approximately 15 per cent chromium and not over 2.5 per cent carbon show marked oxidation resistance and find applications in such parts as grate bars. These steels and irons are discussed in Volume II.

44. High-chromium Corrosion- and Oxidation-resisting Irons and Steels Containing More than 16 Per Cent Chromium.—The next group includes chromium from 16 to 22 per cent and owes its importance almost entirely to corrosion and oxidation resistance. The carbon content is kept to an economical minimum to avoid hardness greater than that demanded and to enhance corrosion resistance as much as possible. These alloys, frequently called stainless irons, are widely used in chemical industries and in certain decorative work. Improved cutlery steels with 0.70 per cent carbon are also produced in this chromium range. With approximately 20 per cent chromium and 2.5 per

cent carbon, cast iron is produced which finds its greatest usefulness in furnace parts involving high-temperature duty.

With more than 22 per cent chromium, some further increase in corrosion resistance occurs, and the oxidation resistance is markedly improved. The carbon is generally kept to a minimum, and the product finds its greatest use where oxidation resistance is the prime factor. These alloys are generally known as chromium irons and, either with or without modifications, form a large proportion of the cast articles used at high temperatures. With 25 per cent chromium and 3.5 per cent carbon a cast iron results which exhibits for many applications a wear resistance equal to that of any other metallurgical product.

By the addition of certain other alloys, steels containing more than 12 per cent chromium are produced which may be predominantly austenitic at room temperature. In this category the chromium-nickel austenitic steels (a well-known example is the low-carbon, 18 per cent chromium, 8 per cent nickel steel), the chromium-manganese austenitic steels with or without copper, and a combination of any or all of these modifications are found. The entire subject of austenitic steels is in itself a major chapter in modern metallurgy. The steels are characterized by high ductility which, combined with their corrosion resistance, renders them useful for many applications. The metallurgist is confronted with many problems, most of which can be traced to the instability of austenite and the presence of ferrite and carbides together with the austenite in the microstructure. The metallurgy of these steels and irons is so special that no attempt at generalization is made here, the subject being treated at length in subsequent chapters in Volume II.

B. GENERAL EFFECTS OF CHROMIUM IN MANUFACTURE AND HEAT TREATMENT

45. Manufacture of Chromium Steels.—The production of chromium steels in the various types of melting furnaces is in general distinct from similar production of carbon steels. This is due primarily to the fact that chromium combines readily both with carbon and with oxygen. Steels with up to 3 per cent chromium have been produced in the open-hearth furnace. Special precautions such as thorough initial deoxidation and late ferroalloy addition to a hot bath are necessary to avoid undue

chromium loss if the chromium exceeds 1 per cent. With 1 per cent chromium or less the practice is not materially different from that used for high-grade low-alloy steel, chromium generally being added immediately before tapping in the form of 70 per cent ferrochromium with an appropriate carbon content. Chromium tool steels, like other tool steels, are generally made in an electric furnace, the arc furnace being used in most cases and the induction furnace being applied in certain instances. With more than 3 per cent chromium, the electric furnace—either arc or induction—is invariably employed because of the present inability to obtain a non-oxidizing slag together with the necessary high temperature in the finishing period by the usual open-hearth practice, and because crucible melting, except for a few special cases abroad, is extinct. However, experiments are now under way on melting high-chromium steels in special open-hearth furnaces; but this work affects the future rather than the present status of chromium-steel production.

The manufacture of chromium steels in the electric furnace differs, in many details, from plant to plant; hence, no specific description can be given here. In general, care is taken that the final slag be as non-oxidizing and as low in carburizing effect as possible. The chromium is usually added as ferrochromium, frequently of a low-carbon grade, although in some cases chromium-steel scrap is used, and to a limited extent the direct process of reducing chromium from a chromium-ore slag by silicon is employed (see page 22). Care must be exercised in judging the temperature of high-chromium steels as even a few per cent of chromium change the nature of the oxide formed on a molten surface so as to make the temperature estimation difficult for one not experienced. The alloy is usually introduced into the furnace proper, although a small ladle addition is possible. In general, time must be given for the ferrochromium to dissolve and diffuse in the bath.

46. Forging and Working of Chromium Steels.—These involve no particular difficulty so long as the chromium content does not inordinately increase the yield strength of the material at rolling temperature. However, as the chromium content increases beyond 3 per cent, more careful heating and working are necessary. Suitable minimum hot-working temperatures are 950°C. (1740°F.) for the higher chromium steels and 1000°C. (1830°F.)

for the austenitic chromium-nickel steels. In some of the chromium irons and steels, narrow ranges are necessary for satisfactory work; this is particularly true of the more difficult operations such as piercing.

Cold rolling of chromium irons and steels may be carried out in a manner similar to that used for carbon steel of the same tensile strength, but more frequent annealing may be necessary. This depends upon the amount of hardening caused by the cold working; this in turn varies greatly even for the plain chromium irons and steels and still more for the austenitic types. Detailed discussion of this subject will be found in Volume II.

As is to be expected from their physical properties and their response to heat treatment, chromium irons and steels of suitably selected analysis are readily fabricated. Such operations as shearing, punching, machining, and cold forming may be applied with the same degree of success as to ordinary irons and steels with corresponding physical properties, although in many cases greater power, sharper tools, and smaller clearances are necessary.

47. Fusion Welding and Oxygen Cutting.—Steels containing 0.3 per cent or less chromium can be welded and cut with practically the same facility as carbon steels of equivalent carbon content and treatment. With chromium contents of 0.3 to 1 per cent the welding properties are not seriously affected provided a suitable rod (for example, a properly coated electrode or a silicomanganese-base oxyacetylene welding rod) and the correct technique are used. As chromium steels are likely to air harden when cooled after welding, it is frequently necessary to follow the welding operation by some form of heat treatment. For material containing more than 3 per cent chromium the refractory nature of the oxide formed necessitates the use of a special torch, or special manipulation of the arc and a borosilicate flux or a rod coated with similar material.

Chromium steels can be cut with an oxygen torch although, as the chromium content increases, difficulties are encountered owing to the rate of oxide formation and the refractory nature of the chromium oxide formed. These difficulties can be minimized, however, by means of a zigzag technique and by the use of an iron oxide flux. More details on the welding of chromium and chromium-alloy steels are given in following chapters.

48. Transformation Rates of Chromium Steels.—With the exception of the ferritic high-chromium material, practically every type of chromium steel is sensitive to heat treatment of one form or another. In general, its response to a given heat treatment can be deduced, by those familiar with the behavior of carbon steels, from the equilibrium conditions shown in the constitutional diagram to exist with various carbon and chromium concentrations and at various temperatures. It is necessary, however, to take into account the sluggishness imparted to the solid-phase changes by chromium in solid solution.

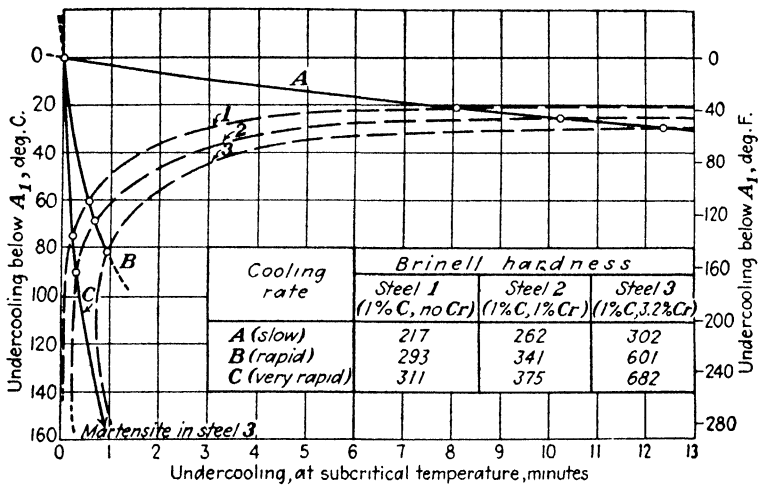


FIG. 56.—Effect of 1 and of 3 per cent chromium on the undercooling time interval of high-carbon steel. (*Bain.*[413])

The nature of the austenite-ferrite transformation has been discussed in detail in the monograph on "The Alloys of Iron and Carbon"[469] of this series (Volume I), the essential point being that the transformation is a time-temperature phenomenon. Chromium even in very small amounts in solution in the austenite markedly increases the time for a given transformation at a given temperature. This subject has been dealt with at length by Bain.[413] Figure 56 shows the effect of 1 and of 3 per cent chromium on the undercooling time interval for high-carbon steels cooled at a constant rate from the same temperature. This effect of chromium of increasing the time interval is of the greatest importance. It means that for a given rate of cooling

martensite and the finer forms of pearlite are much more readily produced if appreciable amounts of chromium are present. Moreover, these finer forms of pearlite (troostite and sorbite) are likewise obtained not only in small rapidly cooled or quenched sections but also in large sections. When large sections are cooled the heat is extracted at the surface and, owing to limitations in heat transfer from the center to the surface, the rate of cooling of the interior of a mass of steel is definitely limited. With chromium, the slower rate of cooling obtained under these conditions is still sufficient to produce either a martensitic or a fine-pearlitic structure, depending upon the mass of the section involved and on the rate of cooling of the surface. Thus, the effect of chromium which renders the transformation sluggish is responsible for pronounced hardenability and deep-hardening characteristics. The effect is of such a large order of magnitude that even fine-grained steels containing chromium are deep hardening as compared with carbon steels of equivalent carbon content.

49. Heat Treatment of Chromium Steels.—Up to approximately 0.3 per cent chromium, the response of the steels is not materially different from that of similar plain carbon steels, although even with these small amounts a less drastic quench is necessary to produce the same hardness, and a greater depth of hardness is achieved. As the chromium increases from 0.3 to 1 per cent, the effect of the alloy on the response to heat treatment becomes extremely marked. As can be seen from the ternary diagrams, the eutectoid carbon composition is lowered so that the steels behave in a manner somewhat analogous to that of steels with higher carbon, although the absence of the equivalent amount of carbide results in greater ductility for a given strength. The presence of chromium in these amounts also increases the sluggishness of transformation, thus markedly reducing the cooling rate from above the *Ac* temperature necessary to produce a structure corresponding to a given hardness or strength, and likewise markedly increasing the depth of penetration and decreasing the mass effect obtained under such conditions. Moreover, with chromium in the range in question, the production of fine pearlite (sorbite) with its correlated strength and ductility is frequently achieved by simple air cooling. Again, in these steels more time is necessary to produce changes in the

unstable subcritical structures, so that higher tempering temperatures or longer tempering times, or both, are necessary to obtain the same structure and corresponding strength found in steels not containing chromium.

In considering the effect of heat treatment on steels containing from 1 to 3.5 per cent chromium, the same general observations hold true. The steels with as little as 0.20 per cent carbon are subject to an appreciable degree of air hardening in lighter sections. With carbon up to 0.30 per cent, the steels respond to air cooling, even in sections as heavy as railheads, in such a manner as to result in relatively high hardness, the low carbon accounting for their excellent ductility. Chromium from 1 to 3 per cent is frequently used to improve depth-hardening characteristics of tools, dies, bearings, and the like.

The effect of chromium contents between 3.5 and 9 per cent is much less marked for a given increase than that in the region up to 3.5 per cent. Steels in this category, except those in the very low carbon range, are so susceptible to air hardening that an annealing treatment is required to avoid a martensitic structure with its concomitant physical properties. A drastic quench is not necessary to obtain a very high degree of hardness. Steels containing 0.15 per cent carbon or less readily respond to heat treatment for improvement of their properties and are markedly different from plain low-carbon steel in this respect.

As the chromium content increases, the effect of small amounts of carbon becomes increasingly important. A steel with 0.30 per cent carbon and 12 per cent chromium is roughly of the eutectoid composition. Of these higher chromium materials the eutectoid and hypoeutectoid steels respond to heat treatment exactly as would be expected from observations made on the plain carbon and lower chromium steels, and the hypereutectoid steels act in a similar manner down to a limiting carbon content, as shown in Fig. 56, page 106. This limiting carbon content corresponds to the disappearance of the gamma-phase region (Fig. 7, page 31). Response of a steel to heat treatment depends upon the austenite-ferrite transformation,* and with the suppression of the austenite no such transformation is possible. It has been seen in the constitutional diagrams that the existence of the austenite phase at

* This is true if age hardening is not considered as a heat treatment. Age hardening does not depend upon the austenite-ferrite transformation.

a given temperature is a function of the chromium and carbon contents, and that, as the chromium increases, more and more carbon is necessary to insure the existence of the austenite phase and the susceptibility to heat treatment. From the practical aspect the matter is further complicated by the existence of a two-phase region wherein a certain percentage of the material transforms to austenite at a suitable temperature, the remainder being ferrite. Even in plain chromium steels it is rare for any but minute percentages of austenite to be retained as such on rapid cooling, so that susceptibility to heat treatment may be considered to be a direct function of the relative amounts of austenite and ferrite, with chromium and carbon in solid solution, at quenching temperature. The same reasoning applies to chromium steels with 16 to 22 per cent chromium and more, although the amount of carbon necessary to produce complete transformation to austenite at elevated temperatures for purposes of quenching becomes increasingly greater, and the range of alloys in which the carbon is low enough so that the alloy remains ferritic at all temperatures is much greater.

When the high-chromium, medium- and high-carbon steels are modified by an austenite-forming element, a fully austenitic state may be readily produced at suitable temperatures, with the result that such steels may be susceptible to heat treatment. When the amount of austenite-forming elements becomes sufficiently great, it is possible to retain the austenite as such to a large degree by rapid cooling even in low-carbon steels. Such steels are susceptible to heat treatment in the usual sense by slow cooling or in the tempering or "reheating after quenching" operation. However, this frequently involves many complications, which are discussed in detail under the appropriate chapter headings in Volume II.

C. GENERAL EFFECTS OF CHROMIUM ON PHYSICAL AND CHEMICAL PROPERTIES

The physical properties of chromium steels are definitely related to their constitution and heat treatment, and are even more greatly affected by the carbon content than are the corresponding properties of plain carbon steels. Chromium steels are an excellent illustration of the thesis that the best combination of strength and ductility, or hardness and toughness if this nomen-

clature is preferable, may be obtained in steels with the lowest carbon content for a given tensile strength.

The chemical properties of chromium steels are outstanding; one of the most important effects of chromium is its ability to impart, when alloyed with iron, various degrees of resistance to oxidizing chemical attack.

50. Effect of Chromium on Physical Properties.—The fact that the best combination of strength and ductility is obtained in chromium steel with the lowest carbon content for a given tensile strength holds throughout the entire range of chromium and carbon contents. In steels in the engineering range, containing up to 3.5 per cent chromium, for a given heat treatment and a given carbon content, both the strength and the ductility are improved by the chromium. In the tool-steel range, hardness and wear resistance are increased; also the resistance to impact is increased when compared with that of carbon steels. Moreover, as is common with alloy steels in general, the properties, by the selection of a suitable composition and heat treatment, may be varied in a range even wider than that of the corresponding plain carbon steels. By the addition of other suitable alloying and grain-refining elements to the chromium steels, the combination of strength and ductility may be further improved. The shock resistance, determined at low temperatures, is increased by chromium, particularly in combination with other elements; this improvement results from the action of the alloys in shifting the range of low impact toughness to lower temperatures (see "The Alloys of Iron and Carbon,"[478] Volume II, page 625). The same applies to an even greater degree to steels with 3.5 per cent to 9 per cent chromium. Certain other physical properties may be markedly improved by suitable compositions in this range —particularly the magnetic permeability and wear resistance. Steels in this category, with suitable carbon content, may also be produced in a relatively soft condition, permitting cold bending, forming, shearing, and the like. The creep strength of steels in this category is appreciably improved, particularly when the chromium is used together with small amounts of tungsten or molybdenum.

As the chromium increases beyond 12 per cent, the strength and ductility in suitable carbon ranges continue to be improved, with the possibility of further improvement in wear resistance

and creep strength. Some further benefits are noted in the medium and higher carbon ranges with an increase of chromium up to 22 per cent. As the chromium passes 12 per cent, the possibilities of relatively soft material in the low-carbon ranges appear, and with constant low carbon content this ability to produce soft material suitable for deep stamping continues with increase of chromium up to 22 per cent. With increasing chromium, higher than 22 per cent, the hardening effect of the chromium in the lattice *per se* becomes an increasingly important factor and tends to compensate for the elimination of transformation hardening so that it is more difficult to obtain these alloys in the very soft condition. The diagram Fig. 57 prepared by Thum[475] shows the effect of increasing chromium content on the properties of annealed irons and steels containing 0.10 per cent carbon.

The addition of austenite-forming elements increases hardness and strength until a sufficient amount of such elements is present so that austenite is retained in preponderant amounts on rapid cooling, resulting in ductility of a very high order together with relatively high strength, not only at room temperature, but also at elevated and subnormal temperatures.

51. Effect of Chromium on Chemical Properties.— When chromium is present in the matrix proper and as carbides, the corrosion resistance of alloys is a function of the chromium content of the matrix. This function is not a direct one, because the resistance to attack increases very slowly with small percentages of chromium but becomes marked when the chromium content reaches approximately 4 per cent and increases very rapidly as the chromium content passes 10 per cent. Naturally, the resistance of chromium steels to chemical attack is limited to specific types of corroding media, and in general the oxidizing types are more definitely resisted. The best illustration of such a medium is nitric acid and as the chromium increases to amounts of approximately 18 per cent the resistance to nitric acid at certain temperatures is high. It is thought by some that the corrosion resistance of the chromium steels depends upon the formation of a corrosion-resistant oxide film of which chromium oxide comprises a large part. One hypothesis states that, in order that the film be continuous and self-healing, one atom of chromium should be present for each seven atoms of iron as a minimum

condition, and that beyond this chromium content the corrosion problem reduces itself to a matter of rate of solution of the film versus rate of formation of the film. The lack of resistance to attack by dissociated chlorides in the absence of strongly oxidizing

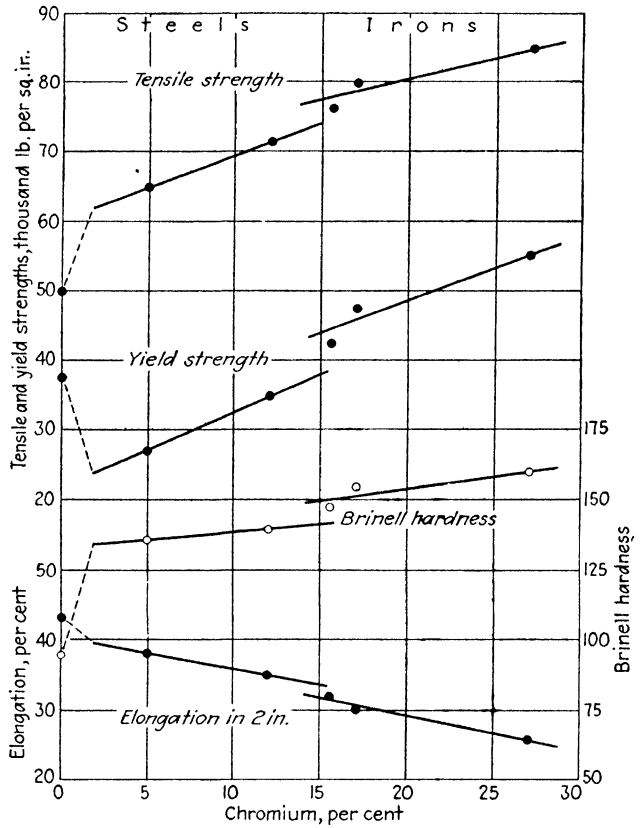


FIG. 57.—Effect of chromium on the mechanical properties of annealed irons and steels containing 0.10 per cent carbon. (*Thum.*[47b])

substances is illustrative of high rate of film solution combined with low rate of film formation of high-chromium steels.

Ferritic chromium steels are resistant to caustics as well as to many acids, and are particularly suitable where the combination of stress and caustic attack is involved. Such steels with 12 per cent or more chromium are resistant to caustic embrittlement encountered in boiler work, although this is not true of the steels when modified with appreciable amounts of austenite-forming elements. However, such elements do increase the resistance to

acids of lower oxidizing power. Resistance to specific corroding media is discussed in subsequent chapters in Volume II.

The resistance of chromium steels to oxidation increases with increasing chromium content. With low chromium contents of the order of 1 to 3 per cent, this is evidenced in the type of scale formed, but the degree of improvement over that of plain carbon steels is small. The oxidation resistance of steels with 3 to 10 per cent chromium, particularly at temperatures corresponding to a

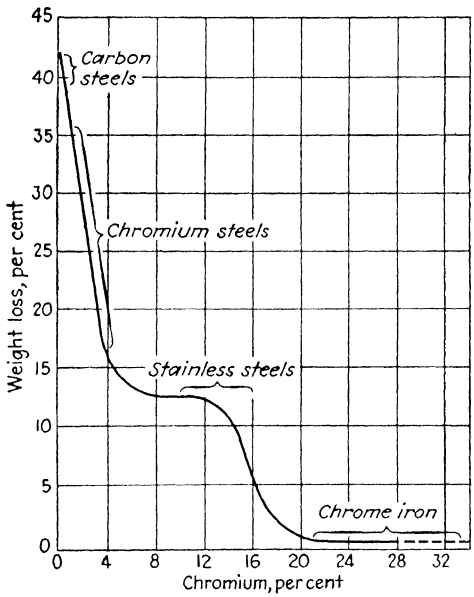


FIG. 58.—Effect of increasing chromium on oxidation resistance. (*MacQuigg, according to Thum.*[47])

dull red heat, is markedly improved, and beyond 10 per cent, improvement analogous to that of corrosion resistance occurs. Improvement beyond 10 per cent is continuous and fairly uniform until the chromium content passes approximately 20 per cent. With this amount of chromium, another marked improvement in oxidation resistance is noted; beyond this content there is further gradual and uniform improvement up to the highest amount of chromium used in commercial work. The accompanying Fig. 58 prepared by MacQuigg shows the quantitative effects. The oxidation resistance of chromium steels is but little affected by the presence of usual alloying elements other than silicon, titanium, columbium, and aluminum.

CHAPTER VI

MANUFACTURE AND HEAT TREATMENT OF PLAIN LOW-CHROMIUM ENGINEERING STEELS

Early Development of Chromium Engineering Steels—Manufacture and Fabrication—Heat Treatment of Low-chromium Steels—Authors' Summary

The low-chromium steels, unmodified by the addition of other alloying elements, were defined previously as those containing up to 3.5 per cent chromium. As already noted, these steels owe their value to their improved properties and increased susceptibility to heat treatment. They find wide application as structural and engineering materials and have been used as rail steels. The low-chromium steels, unmodified, and modified by the addition of manganese, silicon, nickel, vanadium, molybdenum, tungsten, copper, and a few other elements, constitute a large part of the total tonnage of wrought alloy steels produced.

Structural and engineering materials constitute the largest proportion of the plain and modified low-alloy steels now being regularly produced. The former are discussed in this and the next chapter. The manufacture, properties, and uses of the modified low-chromium steels are given detailed attention in Chapters VIII and IX. In addition to these common materials, a small but important tonnage of plain chromium steels containing 3.5 per cent or less chromium is used for ball bearings, dies, and tools. These steels are discussed in Chapter X. Concluding the summary of data on the low-chromium grades is a chapter (XI) on the special-purpose steels which includes those for nitriding, magnets, high-speed tools, armor plate, and other purposes.

A. EARLY DEVELOPMENT OF CHROMIUM ENGINEERING STEELS

As noted briefly in Chapter I, the first application of chromium as an alloy in steel was reported by Berthier[3] in 1821 and by Stodart and Faraday[4] in 1822. It was recognized at that time

that the addition of chromium to steel was greatly facilitated by the use of a chromium-rich alloy, and such alloys containing from 17 to 60 per cent chromium were produced by carbon reduction. The ferrochromium was added to an iron base, and the charge was melted in a crucible. Berthier produced steels containing 0.1 to 1.5 per cent carbon and somewhat over 1 per cent chromium. The low-carbon steels were found to be very similar to steels without chromium and were fairly soft after quenching. The higher carbon grades were found to make excellent knives and razors and were suitable for the development of good damascened surfaces. No further use of chromium in steel was made until after 1850. In 1857 Frémy[7] reported work on ferrochromium.

52. Early Commercial Use of Low-chromium Steel.—The 1865 patent of Baur* and the first reported use of chromium steel in the Eads Bridge at St. Louis have been mentioned in the first chapter. These early steels were made by adding 2 per cent ferrochromium containing about 30 per cent chromium and 3 per cent carbon to wrought iron and melting the charge in a crucible. Tests reported by Thum[235] (1928) showed that the staves for the main arch members of the Eads Bridge had a tensile strength of 115,000 to 140,000 lb. per sq. in., with the following analyses:

Element	Percentage		
	Minimum	Maximum	Average
Carbon	0 64	0 95	0 79
Manganese	0 018	0 23	0 11
Phosphorus	0 007	0 082	0 044
Sulphur	0 006	0 013	0 009
Silicon	0 056	0 19	0 10
Chromium	0 54	0 68	0 61

Following this development, production of similar steels was started at the Jacob Holzer works at Unieux in France.

As reported by Boussingault[13] and by Brustlein,[14] chromium iron and steel had been made at various places prior to and during this period. The Tasmanian Iron Company used a blast furnace to make iron containing 4.42 per cent carbon, 7.05 per cent

* See footnote, p. 2.

chromium, 1.52 per cent silicon, 0.14 per cent manganese, 0.10 per cent phosphorus, and a trace of copper.

In 1866 and 1867, a forge near Medellin in Colombia, South America, also produced a hard chromium-bearing pig iron that was used for stamp mills to crush auriferous quartz. The Medellin pig contained 4.40 per cent combined carbon, no graphite, 0.75 per cent silicon, 1.95 per cent chromium, 0.84 per cent manganese, 0.87 per cent phosphorus, and traces of sulphur, arsenic, nickel, and vanadium. Other analyses gave 2.80 and 3.80 per cent chromium.

53. Early Manufacturing Practice.—Brustlein[14] reported the following practice at the Jacob Holzer works at Unieux. The ferrochromium usually contained 48 to 52 per cent chromium, 7 to 8 per cent carbon, and up to 2 per cent silicon. In melting the alloy with iron in the crucible, a flux of bottle glass, sodium carbonate, or calcium fluoride was used. The steels that contained up to 2 per cent chromium were found to present somewhat more difficulty due to scaling, but were hot worked like carbon steel. Oxides in deep seams or cracks in the ingots were found to be very persistent. Attempts to use ferrochromium as a substitute for manganese in deoxidation were not successful on account of the lack of the formation of a fusible silicate as is the case with manganese. Hammer welds of chromium steels were not satisfactory. In cold working, it was found that the chromium steels hardened to a greater extent than similar carbon steels. The chromium steels were found to be less sensitive to overheating and had less tendency to harden when high carbon was present than steels with correspondingly high manganese. Although the mechanical properties of several chromium steels were reported, the details of heat treatment were not sufficiently adequate to make the results of interest. Armor plate of steel containing 0.6 per cent carbon and 2.2 per cent chromium was considered to be unexcelled at that time. It was found that, in order to give the best results, the steels had to be oil quenched. In projectiles, a steel with 0.9 to 1.4 per cent carbon and 2 to 4 per cent chromium was found to have good properties.

Although the methods for producing chromium steel were fairly well known, a good deal of difficulty seems to have been experienced in producing satisfactory ingots. The steels at that time were usually very low in manganese and often suffered from lack

of thorough melting owing to the low temperatures available. For this reason, although chromium steels were shown to have good properties in some cases, their adoption for general industrial purposes was retarded.

Arnold[16] in 1888 reported on the properties of chromium in Bessemer steel tires. These steels contained approximately 0.30 per cent carbon, 1.50 per cent manganese, and 0.50 per cent chromium. Apparently the steel was of sufficient merit to justify the production of several hundred tons for this purpose.

Up to 1890, no systematic tests had been carried out to determine the effect of chromium in steel, and the attempts to utilize chromium steels were spasmodic. The history of this period was summarized by Howe.[18] Although chromium was found to be definitely beneficial for several applications where high hardness or relatively great strength was required, the widespread development of chromium appears to have been hindered greatly by the overenthusiastic efforts of some of its proponents and by the lack of any fundamental knowledge of the mechanism by which the benefits were produced. On account of the high carbon content of the ferrochromium the compositions tested were necessarily limited to certain ratios of carbon and chromium, and therefore the need for lower carbon was not appreciated until after methods for the production of low-carbon ferrochromium were developed.

B. MANUFACTURE AND FABRICATION

In a number of the operations connected with the melting and mechanical working of low-chromium steels, and in fabricating these materials for industrial use, the processes are similar to those used for other high-grade engineering steels. In some respects, however, the processes differ. In the following sections the various manufacturing and fabricating operations are discussed with special emphasis upon those which differ in detail from the corresponding process for carbon steel.

54. Melting and Ingot Practice.—As pointed out, it was discovered at a very early stage that chromium should be introduced in the form of a chromium-rich ferroalloy to avoid excessive loss of chromium and contamination of the steel with chromium oxide. Although practically all of the chromium engineering steels containing up to 3.5 per cent chromium are now made in the open-

hearth and electric furnaces instead of the crucible, ferrochromium is still considered to be the most suitable form for addition. In general, the chromium steels are made with the same practice as all the high-quality engineering steels.[233]

Good practice in the production of alloy steels in both open-hearth and electric furnaces involves the use of selected scrap and other raw material to avoid contamination with excessive amounts of impurities. In the open-hearth furnace the charge is melted rapidly with early ore additions to avoid excessive oxidation as the finishing period is approached, and the carbon is brought to a point somewhat below that desired in the finished product. The steel is then killed with silicomanganese or some similar initial deoxidizer, and ferrochromium is added and allowed sufficient time to melt and be diffused through the metal. Where additions of more than 1 per cent chromium are made, particular care must be taken to avoid chilling the bath so that the time for melting is not unduly lengthened. The heat is then tapped with additions of ferrosilicon, etc., in the ladle. In the electric furnace somewhat similar practice prevails. The ferrochromium is added after a carbide slag has formed and has been allowed to stand for sufficient time for deoxidation. In acid practice it is advisable to use more than a normal amount of lime to minimize the loss by oxidation. According to Sullivan,[438] the residual chromium in American open-hearth charges has been found to be fairly consistent at about 0.03 per cent for several years.

No special precautions are necessary in pouring the engineering chromium steels. In general, it has been found that chromium tends to minimize segregation and ingotism,[376] and that the steels are relatively free from a tendency to ingot cracks. In common with high-carbon and the harder alloy steels, the hard grades of chromium steels are subject to flakes or hair cracks. A host of investigators, including Rapatz[128] and Hultgren,[161] have worked on this subject without reaching entirely satisfactory conclusions. In the relatively low carbon plain chromium engineering steels, flakes are seldom encountered, and the tendency to produce them is minimized by careful deoxidation, slow pouring, and slow cooling. In line with the concept that anything which increases air hardening increases the tendency to flake formation this tendency has been observed to increase with chromium, up to about 2.5 per cent chromium, in the medium-

carbon steels, but above this amount the occurrence of flakes is seldom encountered.

55. Hot and Cold Working.—In reheating for rolling, the chromium steels require no special practice; indeed, they are to some extent less sensitive to overheating and burning. However, the scale formed on chromium steels is relatively tough and should be reduced to a minimum.[254] Although the high-carbon and high-chromium steels are somewhat stiffer to roll, the difference between chromium and carbon steels is relatively small so that special mills and other equipment are not necessary.[229,386] In small sections the tendency of the chromium steels to be somewhat harder makes it necessary to avoid fins and overfills as they result in seams and overlapping in the finished bar. Finishing temperatures must be controlled for all alloy steels; the low-chromium grades are, however, not so sensitive to variations as are some of the other alloy steels. In most of the engineering and automotive types of chromium steels the variation in hardness and brittleness owing to differences in finishing temperature is small as the compositions used for most applications are relatively insensitive to minor changes in air cooling.

However, in 1 per cent chromium steel when the manganese is high, or in the high-carbon chromium steel, the finishing temperature must be adjusted to the analysis to avoid excessive hardening and brittleness. On account of the rapidity with which chromium steels can be softened at relatively high subcritical temperatures, either on initial cooling or on reheating, a slow cooling on the finishing bed results in further reduction of hardness and brittleness. Although the higher carbon steels, as mentioned before, are somewhat subject to seams as a result of fins and overfills, this tendency is not particularly strong in the medium or lower carbon grades so that the grinding and chipping required to produce clean billets and bars are usually no greater than in other steels of this quality.

Published data on the effect of cold working the low-chromium engineering steels are not available except for the high-carbon tool-steel grades covered in Chapter X. In general, the cold-rolling practice for the lower chromium steels is very similar to that for plain carbon steel, the only significant difference being a slightly greater tendency to work harden. Slightly higher annealing temperatures are required to restore full elasticity, and the

elastic limit is somewhat higher. Springs of cold-worked chromium steel can be operated at higher temperatures than carbon steels.

56. Welding and Cutting.—Welding of the low-chromium engineering steels presents no special problems of technique by either the arc or the oxyacetylene process. As pointed out by Hatfield,[451] if suitable precautions are taken, which may entail the use of a flux with steel containing more than 3 per cent chromium, sound welds are produced. In the higher carbon, higher chromium compositions the steels air harden after welding, but with reasonable skill and care there is no danger of cracking. Critchett[315] and Tull[348] have emphasized that chromium steels are usually used in fairly high strength ranges so that welds of this type of material should be heat treated, preferably by normalizing, in order to obtain the best properties.

Chromium is also used in filler rods for making high-strength welds and for wear-resisting surfaces. Zeyen,[352] in welding chromium-molybdenum aircraft tubing found, in comparing several types of rod, that the best physical properties resulted from the use of a 2 per cent chromium-steel rod. Délong[448] reported the use of a high-carbon chromium steel for building up battered rail ends. This type of rod requires the strong air-hardening property of chromium and is usually more successful with medium-carbon and high-alloy contents.

Flame cutting is a fast and economical method that is rapidly supplanting many machining processes in structural work as well as in foundries and steel mills, and also in demolition operations. With up to 3.5 per cent chromium in the steel, there is no difficulty in burning the metal, and the slag flows freely. Moreover there is little danger of cracking. The higher carbon and chromium steels air harden and require a suitable treatment to soften the kerf. The softening treatment requires little time or heat so that it may be readily carried out with a suitable torch.

57. Shearing, Stamping, Punching, Forming, and Riveting.—Shearing of chromium steel is successfully carried out industrially. When properly made, the steels have adequate ductility so that shearing cracks are not produced. However, size plays an important rôle, and difficulties may be experienced in heavy sections. The scale of chromium steel is fairly tight, but it is

relatively light and does not cause excessive wear of the dies in stamping operations. Although the effect of chromium is relatively small in comparison with that of silicon, it has a strong tendency to reduce strain aging. Forming may be carried out as on most of the alloy steels of equivalent strength. The steel does not have any abnormal cold-working characteristics, and in sections commensurate with the strength it may be flanged cold or hot.

Fabrication of chromium steel by riveting requires no special precautions other than those observed for all high-strength steels. In order to utilize the high strength to the fullest advantage, it is necessary to use rivets of similar strength. The development of strong rivet steels has presented a special problem. The common high-strength steel rivets tend to loosen on cooling if not driven long enough, and to fail at the head junction if driven too long. Special steels have been developed for this purpose. The chromium-manganese-silicon steel, described in a later chapter, transforms at a high temperature so that the rivets are tight, and it has the high strength suitable for the purpose.

58. Machinability.—Although an enormous amount of work has been done on machinability of steel and cast iron, the fundamental principles underlying the process have not been sufficiently clarified to indicate clearly the properties necessary for good machinability. Although certain steels and certain heat treatments may be shown to be unquestionably superior for a given machining operation, no general formula has been devised to indicate whether a steel will be suitable for even similar types of work. For this reason, claims regarding the beneficial or adverse effect of alloy additions are usually based on specific, and often prejudiced, conditions. Only two factors determining machinability of engineering alloy steels appear to be well established. The hardness should be sufficiently high to avoid tearing and rough finishes, and sufficiently low to reduce the amount of energy required. The second factor is that large grain size and relatively low notch-impact value appear to be essential to good machinability. By those in the gear and allied industries the chromium steels are generally recognized as superior to many other alloy engineering steels from a machining standpoint. Moreover, they are relatively easy to anneal to obtain structures having maximum machinability. It should be further noted

that Widmanstätten structures are uncommon in chromium steels. This further increases ease of processing for machinability.

Jones[98] made lathe tests on a 3 per cent chromium steel treated to give Brinell hardness values of 245 and 385. Under his conditions of testing (feed $\frac{1}{128}$ in., depth $\frac{1}{8}$ and $\frac{3}{16}$ in., speed 93 sec. per in. for 385 Brinell and 52 sec. per in. for 245 Brinell, specimen

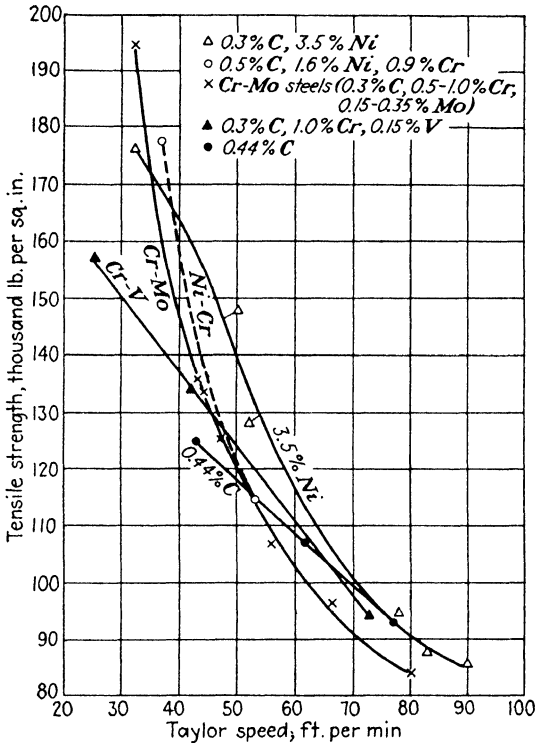


FIG. 59.—Relation of Taylor speed to tensile strength in rough turning quenched and tempered special steels. (*French and Digges.*[178])

0.70 in. in diameter), 3 per cent chromium steel was superior to high-nickel and chromium-nickel steels. French and Digges[178] made heavy cuts ($\frac{3}{16}$ in. depth, 0.028 in. feed) with the results shown in Fig. 59. It will be seen that chromium steel was found to be slightly inferior to nickel steel at low hardness and to chromium-nickel steel at high hardness. The differences were reported to be of a lower order than that found between different grinds of the tool. The difficulty of estimating machinability is illustrated by later work on these steels in which their relative

positions were reversed when light cuts were taken. Plagens[397] also tested chromium steels along with other alloy steels, but differences in hardness make it impossible to evaluate the effect of chromium.

These reports confirm casual observations of the machinability of chromium steels. When softened to a suitable hardness, chromium steels do not appear to be more or less difficult than other comparable steels. In the rolled condition where hardness rises with the chromium content, chromium does not appear to aggravate the difficulty of machining except in high-carbon grades having a strength in excess of 180,000 lb. per sq. in. In these grades it has been found that 3 per cent chromium steel can be machined at a higher hardness than 2 per cent chromium steel. This condition is not often encountered and does not change the conclusion that, in general, chromium has no appreciable influence on machinability.

C. HEAT TREATMENT OF LOW-CHROMIUM STEELS

It is shown in Chapter IV that certain of the early workers, notably Osmond (page 81), concluded that, if steel is cooled (not quenched) from a sufficiently high initial temperature, the Ar_1 transformation is lowered by the addition of chromium, and that under certain conditions the lowering is sufficient to permit the formation of martensite, *i.e.*, the steel is air hardening. Osmond[17] noted also that even a small amount of manganese greatly increases the lowering of the transformation temperature upon cooling. These findings, which were obtained from steels made by Hadfield,[19] were denied by Carpenter;[34] this incited a controversy in which Osmond and others[28,33 37] participated.

It is now well known that Osmond was correct in concluding that chromium is able to produce air hardening, but not for the reason then given. By its very nature the process of transformation includes the factor of time; consequently any explanation of the behavior of steel in heat treatment based on transformation temperature alone must be incomplete. Quantitative information on the rate of transformation of steel was supplied by Davenport and Bain[272] and other workers in the same laboratory;[446] this has been discussed in detail by Epstein.[469] By way of review it may be stated that, in general, the effect of addition elements, such as chromium, is to lower the rate of

transformation; this is the essential point. Below a certain temperature, austenite no longer is able to transform to ferrite and pearlite, but only to martensite. Thus, in the process of ordinary air cooling, if the transformation is so strongly delayed—which is equivalent to stating that the transformation velocity constant is small—that austenite persists to the temperature range in which only martensite can form, the steel is air hardening. It is also possible, with other values of the velocity constant, that transformation begins before the steel has reached the temperature range of martensite formation. In this instance, hardening is not complete. The other extreme exists if the velocity constant is sufficiently large to permit complete transformation to ferrite and pearlite before the temperature range of martensite formation is reached. This is true of carbon steels, for they certainly do not air harden.

The foregoing picture is not quite complete, but is enough so at least to indicate the nature of the mechanism of transformation. That such a mechanism operates is worth remembering during consideration of interpretations of the behavior of steel in heat treatment that are based on what is sometimes called "the effective transformation temperature." Since a large part of the work on the heat treatment of chromium steels was conducted before the mechanism of transformation was understood, it is nearly impossible to avoid reference to such interpretations.

59. Early Work on Transformations in Low-chromium Steels. Moore[50,90] investigated the critical ranges of chromium steels containing up to 6.42 per cent chromium and from 0.25 to 0.57 per cent carbon, with slow and rapid cooling, as shown in Chapter IV, Table 9. Although Moore determined that the points on heating were raised by chromium, and that Ac_1 was higher than Ac_2 in steels containing more than 2 per cent chromium, his rates of cooling were too slow to develop the lower transformation which produces martensite.

McWilliam and Barnes[49] determined the critical temperatures on cooling at rather slow rates. With the rates of cooling involved, a variation in the initial temperature from 950 to 1100°C. (1740 to 2010°F.) was found to be insignificant. The eutectoid composition of 2 per cent chromium steel was indicated to be in the neighborhood of somewhat more than 0.65 per cent carbon (see page 82).

In 1916, Edwards, Greenwood, and Kikkawa[64] investigated the effect of initial temperature and cooling rate on a steel containing 0.63 per cent carbon, 0.17 per cent manganese, 0.07 per cent silicon, and 6.15 per cent chromium. The demonstration that higher initial temperature caused a lowering in the critical hardening rate led to further work on the lower chromium steels.

The first systematic study of the rates of cooling in the steels containing less than 3.5 per cent chromium was carried out by Murakami[75] in 1918. Steels containing graduated amounts of carbon and chromium were heated to initial temperatures of 900 to 1200°C. (1650 to 2190°F.) and cooled at different rates. The normal rate shown in Table 20 amounted to 3.9 to 4.3 min. to cool from 750 to 600°C. (1380 to 1110°F.). The fast rate required 27 to 30 sec. for the same range of temperature. The transformation was measured by the magnetic susceptibility in an apparatus designed by Honda.

It will be noted that all steels containing up to 3.5 per cent chromium when heated to 900°C. (1650°F.) transformed at the normal pearlite temperature on cooling at the normal rate [about 0.6°C. (1.1°F.) per sec.], and that steels with slightly over 3.5 per cent, such as steel 16 containing 0.27 per cent carbon and 4.44 per cent chromium, transformed at the lower temperature. Similar results were found when steels were heated to 1000 and 1200°C. (1830 and 2190°F.) and cooled at the normal rate. When cooled from 1200°C. (2190°F.) at the fast rate [approximately 6°C. (11°F.) per sec.], transformation at the lower temperature took place in 0.30 to 0.60 per cent carbon steels containing about 1.5 per cent or more chromium, but as the carbon was increased the amount of chromium required to produce lowering of the transformation was increased to about 4 per cent chromium at 1.5 per cent carbon. Murakami[75] found that the magnetic change point of cementite at 210°C. (410°F.) was lowered to 150°C. (300°F.) in low-carbon steels containing less than 1 per cent chromium and in high-carbon steels containing less than 2 per cent chromium. In higher chromium steels the carbide point was not found. The lowering and disappearance of the cementite point were considered to result from the formation of a double carbide, and microexamination led him to the conclusion that several double carbides were formed, depending on the carbon and chromium contents. The double carbides (see

TABLE 20.—EFFECT OF COOLING RATE ON CRITICAL POINTS IN LOW-CHROMIUM STEELS*

Sample No.	Composition, per cent		Initial temperature, °C.	Cooling rate†	Critical point, °C.	
	C	Cr			Ar_1	Carbide point
C	0 28	Nil	900	Normal	660	210
			1000	Normal	650	210
			1200	Normal	640	210
			1200	Fast	540	210
12	0.28	0 44	900	Normal	670	150
			1000	Normal	665	150
			1200	Normal	660	150
			1200	Fast	530	150
13	0.30	1.44	900	Normal	770	
			1000	Normal	695	
			1200	Normal	690	
			1200	Fast	530	
14	0 27	1.81	900	Normal	710	
			1000	Normal	705	
			1200	Normal	680 to 530	
			1200	Fast	500 to 410	
15	0.24	2 84	900	Normal	710	
			1000	Normal	700	
			1200	Normal	440	
			1200	Fast	390	
16	0 27	4 44	900	Normal	690 to 390	
			1000	Normal	380	
			1200	Normal	370	
			1200	Fast	250	
28	0 68	0 92	900	Normal	670	150
			1000	Normal	660	150
			1200	Normal	640	150
			1200	Fast	550	150
29	0 75	2.12	900	Normal	675	
			1000	Normal	670	
			1200	Normal	650	
			1200	Fast	560 to 240	
30	0 76	2 82	900	Normal	685	
			1000	Normal	675	
			1200	Normal	650	
			1200	Fast	560 to 80	
31	0.67	4 74	900	Normal	700	
			1000	Normal	690	
			1200	Normal	640	
			1200	Fast	570 to 80	

TABLE 20.—EFFECT OF COOLING RATE ON CRITICAL POINTS IN LOW-CHROMIUM STEELS.*—(*Continued*)

Sample No.	Composition, per cent		Initial temperature, °C.	Cooling rate†	Critical point, °C.	
	C	Cr			Ar_1	Carbide point
39	0 98	0 86	900	Normal	680	150
			1000	Normal	670	150
			1200	Normal	660	150
			1200	Fast	530	150
40	0.97	1 91	900	Normal	680	
			1000	Normal	670	
			1200	Normal	655	150
			1200	Fast	540	150
41	1 05	2 83	900	Normal	690	
			1000	Normal	675	
			1200	Normal	670	
			1200	Fast	520	
42	0 95	4 42	900	Normal	680	
			1000	Normal	665	
			1200	Normal	660	
			1200	Fast	80	
50	1 49	1 12	900	Normal	660	210 to 150
			1000	Normal	660	210 to 150
			1200	Normal	655	210 to 150
			1200	Fast	520	210 to 150
51	1 48	1 62	900	Normal	675	150
			1000	Normal	670	150
			1200	Normal	660	210 to 150
			1200	Fast	450	210 to 150
52	1 46	2 0	900	Normal	665	150
			1000	Normal	665	150
			1200	Normal	660	150
			1200	Fast	470	210 to 150
53	1 33	2 83	900	Normal	660	
			1000	Normal	655	
			1200	Normal	655	
			1200	Fast	460	150
54	1 38	4 72	900	Normal	705	
			1000	Normal	700	
			1200	Normal	700	
			1200	Fast		

* Murakami [75]

† Normal rate, approximately 0.6°C. (1.1°F.) per sec.; fast rate approximately 6°C. (11°F.) per sec.

Chapter III, page 50) were considered to have the following formulas:

$$\text{alpha} = (Fe_3C)_{18}\cdot Cr_4C$$
$$\text{beta} = (Fe_3C)_9\cdot Cr_4C$$
$$\text{gamma} = Fe_3C\cdot Cr_4C$$

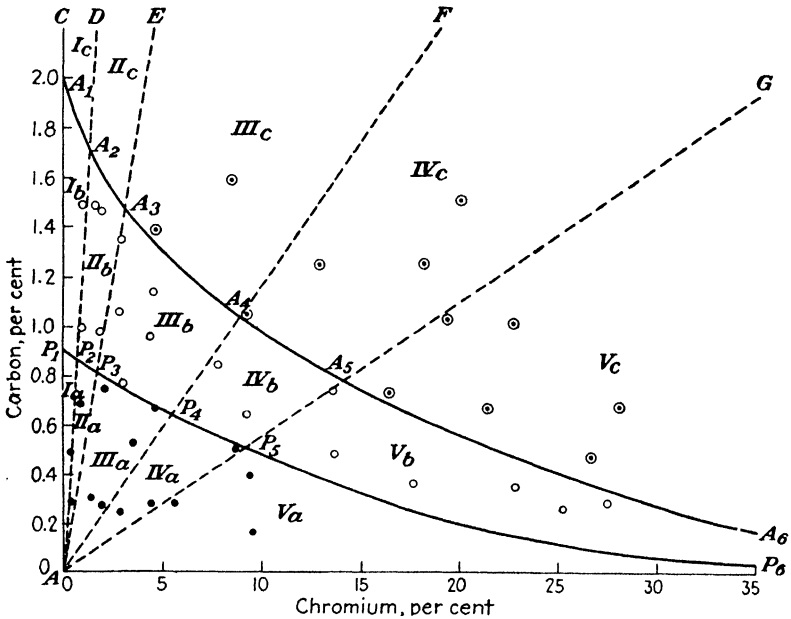


FIG. 60.—Constitutional diagram of the low-carbon chromium steels. (*Murakami.*[75])

As shown in Fig. 60, he divided the chromium steels into five groups as shown below. The lines A and P in the figure represent respectively the limit of solubility of carbide in austenite and the limit of solubility of carbide at the eutectoid temperature. The constituents in each group are as follows:

Group	Constituents	Transformation temperature, °C.
I	$Fe + Fe_3C + (Fe_3C)_{18}\cdot Cr_4C$	700, 210, 150
II	$Fe + (Fe_3C)_{18}\cdot Cr_4C + (Fe_3C)_9\cdot Cr_4C$	700, 150
III	$Fe + (Fe_3C)_9\cdot Cr_4C + Fe_3C\cdot Cr_4C$	700
IV	$Fe + Fe_3C\cdot Cr_4C + Cr_4C$	Under 500
V	$Fe + Cr + Cr_4C$	Under 500 or no A_2

TABLE 21.—EFFECT OF COOLING RATE ON CRITICAL POINTS IN LOW-CHROMIUM STEELS*

Sample No.	Composition, per cent				Cooled from, °C.	Cooling rate, °C. per sec.	Brinell hardness	Critical point, °C.	
	C	Cr	Si	Mn				Ar_2	Ar_1
3	0.33	1.96	0.05	0.14	960	0.385	170	762	738
						0.526	169	762	738
						1.732	173		738 to 690
						2.421	209	.	726 to 702
						6.100	217	. .	704 to 714
						Water	426		
4	0.87	2.08	0.18	0.19	960	0.336	302		710 to 725
						0.930	302	.	709 to 726
						1.000	305		(?)512 to 726
						2.421	340		693 to 726
						3.030	350		665 to 714
						4.035	392		660 to 710
						Water	688		
4	0.87	2.08	0.18	0.19	1200	0.367	298		715 to 736
						2.421	361		642 to 653
						3.030	418	.	628 to 642
						4.855	582		(400)
5	1.00	2.09	0.17	0.29	960	1.345	344		710 to 727
						3.355	364		710 to 726
						4.035	362		690 to 720
						Water	652		661 to 677
11	0.95	4.19	0.32	0.10	960	0.128	259		735 to 746
						0.484	271		716 to 737
						2.421	352		(?) to 737
						6.060	409		661 to 709
						Water	713		
11	0.95	4.19	0.32	0.10	1060	0.150	334		721 to 747
						0.673	370		704 to 723
						2.018	418		670 to 714
						4.032	643		Nil
11	0.95	4.19	0.32	0.10	1160	0.385	366		690 to 701
						1.732	459		630 (weak)
						3.030	596		Nil
						Water	600		
13	0.11	4.72	0.14	0.09	960	0.250	128	785	761
						0.501	134	762	740
						1.211	161		750 to 690
						1.862	278		726 (trace)
						2.421	317		487
						Water	360		
13	0.11	4.72	0.14	0.09	1200	0.138	193		726 to 714
						0.164	278		714 to 702; strong at 513
						0.250	302		Trace at 714; strong at 513
						0.673	321		513
						1.732	330	.	513
						Water	387		
10	0.30	4.02	0.15	0.18	960	0.346	207		716 to 735
						0.526	202		720 to 740
						0.673	418		Weak at 690 to 460; strong at 449
						0.932	463		440
						1.513	470		390
						Water	555		

* Edwards, Sutton, and Oishi.[84]

60. Work on Transformations in Low-chromium Steels, 1920–1930.—Edwards, Sutton, and Oishi[84] in 1920 investigated the critical cooling rates and hardness of several chromium steels

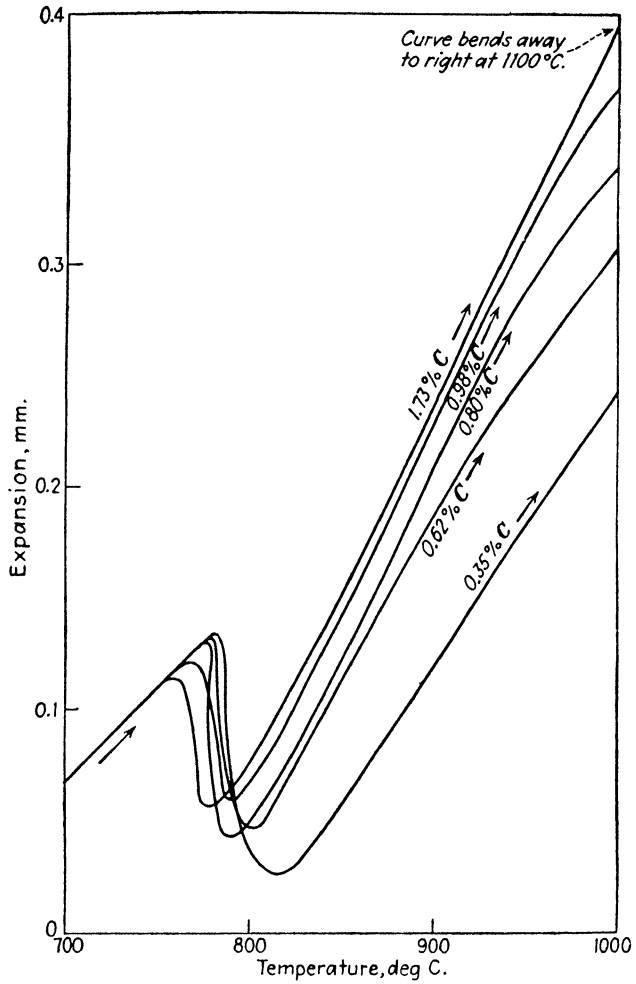


FIG. 61.—Dilatometric curves of 1.6 per cent chromium steels of different carbon contents. (*Andrew, Rippon, Miller, and Wragg.*[80])

cooled from various initial tempe atures as shown in Table 21. Thermal studies were made by the inverse-rate method; the cooling rate was determined from the time required to cool from 856 to 546°C. (1573 to 1015°F.). As in the investigation by

Murakami, depression of the critical point, with an initial temperature of 960°C. (1760°F.) and a cooling rate below 6°C. per sec., was found only in low-carbon 4 to 5 per cent chromium samples—Nos. 10 and 13. With higher initial temperature, depression of the transformation was found in sample 10 containing 0.87 per cent carbon and 2.08 per cent chromium, as well

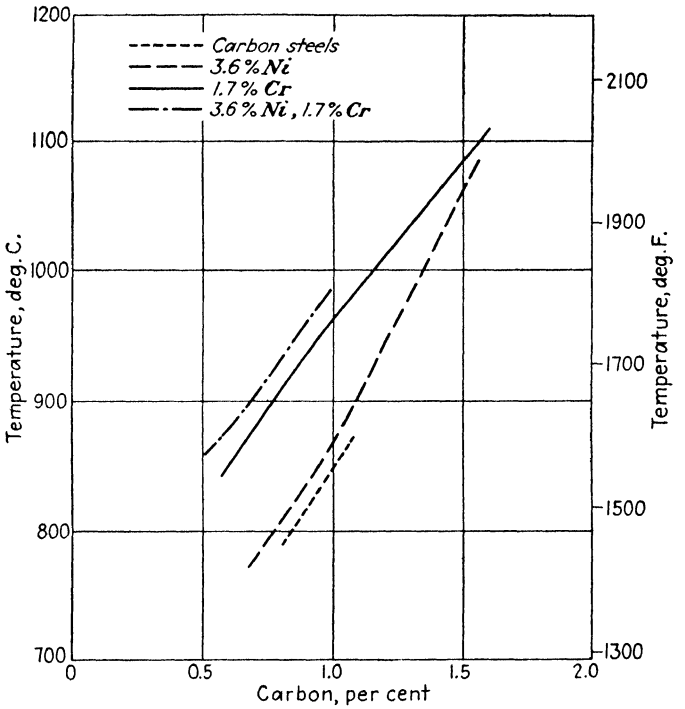


FIG. 62.—Temperature at which "carbide expansion" is completed. With lower carbon content carbide expansion is complete at Ac_3. (*Andrew, Rippon, Miller, and Wragg.*[80])

as in sample 11 containing 0.95 per cent carbon and 4.19 per cent chromium. The structures found in these steels were sorbitic when the transformation occurred at the high temperature, and martensitic at the lower temperature. It will be noted that an abrupt increase in hardness was found when the transformation was lowered and that higher cooling rates caused a further increase in hardness.

Andrew, Rippon, Miller, and Wragg[80] investigated the effect of initial temperature on the critical points of 1.6 per cent chro-

mium steels with varying carbon; their results are shown in Table 22. The samples were cooled in 1.5 hr. from 1000 to 350°C. (1830 to 660°F.) so that no lowering of the transformation was encountered. Dilatometric curves showed an expansion above the critical range as shown in Figs. 61 and 62. This expansion was considered to be due to dissociation or change in the carbide composition and was held to be responsible for lowering of the critical temperature on cooling. Quenched samples were studied by dilatation, electric resistance, and magnetic methods on reheating. Decomposition of martensite was found at 150 to 250°C. (300 to 480°F.), and transformation of austenite was found at 300°C. (570°F.).

Monypenny[89] studied the effect of the initial temperature on steels containing 1.3 to 1.5 per cent chromium and 0.31, 0.75, and 1.02 per cent carbon. Specimens 1 by ¾ in. in diameter were air cooled from high temperatures but no increase in hardness occurred. The same tests were conducted on steels of the following composition:

Steel (see Fig. 63)	Composition, per cent			
	C	Cr	Si	Mn
A	0 37	2 8	0 11	0 48
B	0 70	3 23	0 27	0 52
C	1 28	3 28	0 17	0 22
D	0 14	4 72	0 14	0 12
E	0 53	4 79	0 11	0 25

Results are shown in Fig. 63. More evident effects of higher temperature were found in steels containing 2.8 to 4.79 per cent chromium as shown in the figure. The critical rate [minutes to cool from 855 to 545°C. (1570 to 1015°F.)] of steel *B* rose from 4 to 5 min. at an initial temperature of 900°C. (1650°F.) to 10 to 11 min. at 1200°C. (2190°F.) (Fig. 63).

In 1921, Russell[101] determined the effect of initial temperature on steels with chromium contents up to 3 per cent. The results of his work, determined by inverse-rate and thermal curves, are shown in Chapter IV, Table 12. The rate of cooling was about 1.5°C. per sec. at 800°C. (1470°F.), and at this rate no lowering of the transformation was encountered. Jones[98]

in the same year determined critical temperatures by the inverse-rate method on steels containing up to 3 per cent chromium. With slow rate of cooling he found a slight depression of the pearlite transformation with rise of initial temperature from Ac_3 to 1000°C. (1830°F.) as shown in Chapter IV, Table 11.

In 1922, Jungbluth[112] determined the effect of initial temperature and of rate of cooling on the Brinell hardness of a steel con-

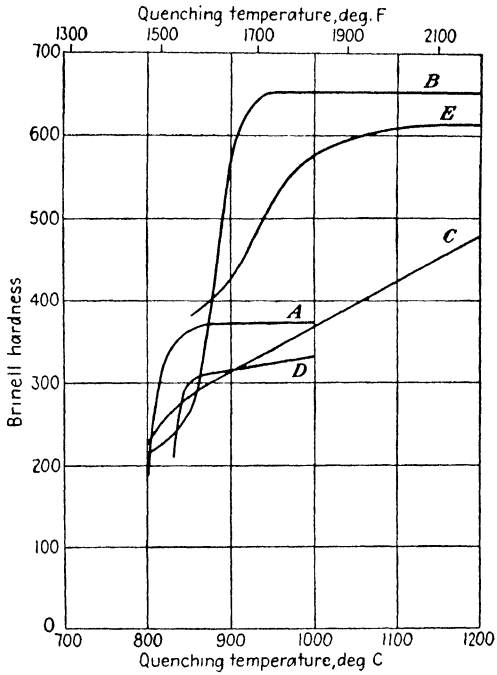


FIG. 63.—Brinell hardness of air-cooled low-chromium steels. See page 132 for composition. (*Monypenny.*[89])

taining 1.6 per cent carbon and 1.6 per cent chromium. As shown in Fig. 64, the maximum hardness was obtained at initial temperatures of 800 to 925°C. (1470 to 1690°F.) with cooling rates from 73°C. (131°F.) per sec. (water) to 13°C. (23°F.) per sec. [lead at 320°C. (610°F.)]. The cooling rate was based on the time required to cool from 800 to 400°C. (1470 to 750°F.). With higher initial temperature and cooling rate than were required to produce maximum hardness, austenite was retained. The reversion of the iso-Brinell curves probably results from

the same condition that produced less austenite in the water than in the oil-quenched steels of Mathews.[165]

TABLE 22.—CRITICAL POINTS OF 1.6 PER CENT CHROMIUM STEELS*

Steel	Composition, per cent			Point in heating, °C. Ac_1	Cooled from, °C.	Point in cooling, °C.	
	C	Mn	Cr			Ar_3	Ar_1
C	0 35	0 24	1.56	806	1000	740	730
					960		720
					930	740	730
					856	755	736
						$Ar_{3\,1}$	
D	0 62	0.22	1 67	806	1000	723	
					900	738	
					875	738	
					856	740	
E	0.80	0 28	1 65	781	1000	725	
					890	730	
					806	738	
F	0 98	0.28	1 65	803	930	733	
					898	724	
					832	733	
B	1.73	0 30	1 65	785	998	700	
					916	705	
					870	724	

* Andrew, Rippon, Miller, and Wragg [80]

Mathews[165] demonstrated that high-carbon steels containing 2 to 3 per cent chromium retained more austenite after oil quenching than after water quenching. The specific gravity of oil-quenched steels was higher, the dilatation curve showed an expansion between 400 and 500°C. (750 and 930°F.), and magnetic tests showed a sudden increase in B_{max} after tempering between 400 and 500°C. (750 and 930°F.). It was also found that the amount of retained austenite could be varied by change in section. Mathews' observations were confirmed by Maurer and Schroeter[251] in 1929, as shown in Fig. 65, for a steel (size of section not given) containing 0.93 per cent carbon and 2.03 per

cent chromium. In general, chromium steels retain far less austenite than do alloy steels which have a lowered transformation temperature on heating as well as on cooling. This results in higher mineralogical hardness. The appreciation of the rôle of the retained austenite by industrial metallurgists has resulted in fundamental changes in processing.

Maurer and Nienhaus[225] determined the critical temperatures of a number of steels by the Saladin method at a cooling rate

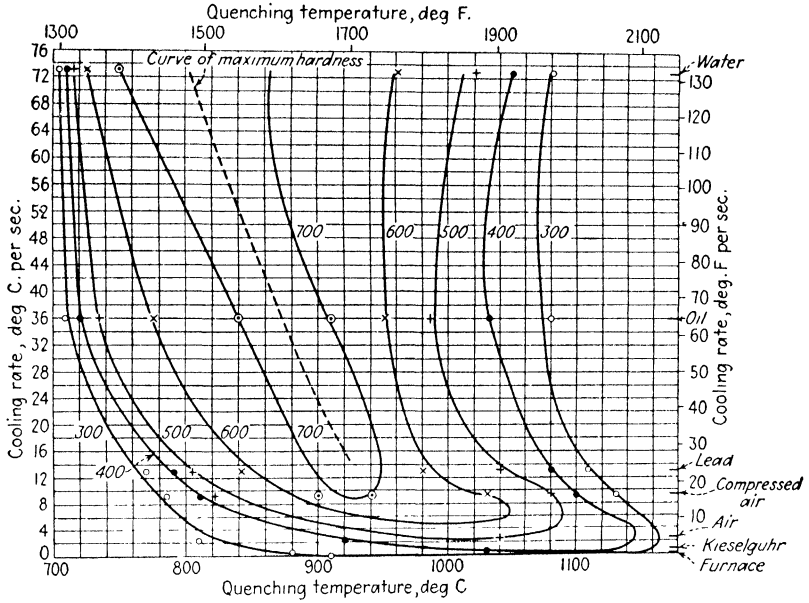


FIG. 64.—Effect of initial temperature and of cooling rate on the Brinell hardness of a 1.6 per cent carbon, 1.6 per cent chromium steel. (*Jungbluth.*[112])

of 5 to 10°C. per min., and by the dilatometric method at a rate of 10 to 15°C. per min. As seen in Chapter IV, Table 14, the small difference in cooling rate had very little effect on the temperature of the transformation.

61. Recent Work on Transformation in Low-chromium Steels. In 1932, Wever and Jellinghaus[378] carried out an extensive investigation of the effect of cooling rates in the low-chromium steels. Their specimens consisted of cold-drawn wire 0.3 mm. in diameter. Thermal analyses were carried out by the method of Wever and Engel,[306] in which the wire is heated electrically in a hydrogen atmosphere, held there 4 to 6 hr., and quenched to

room temperature by turning off the current. Control of the rate of cooling was obtained by changing the gas flow and the diameter of the wire. The cooling rate was determined graphically from the tangent to the cooling curve at 900°C. (1650°F.). Critical cooling rates for steels of various compositions are given in Fig. 66. It was found that the presence of 0.5 per cent

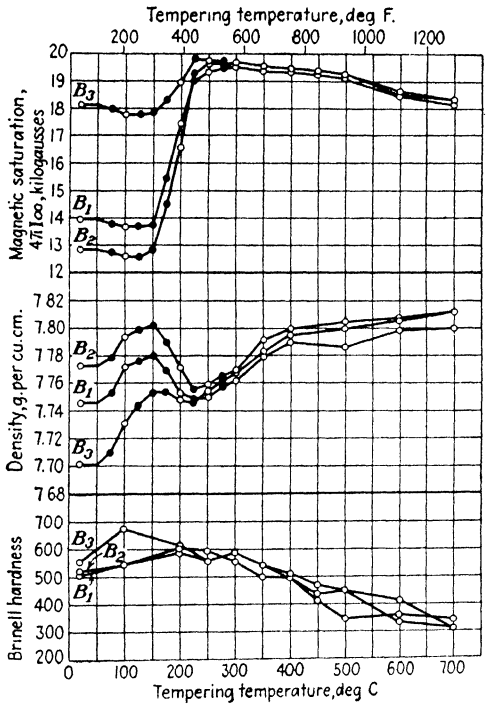


FIG. 65.—Effect of cooling rate on the Brinell hardness, density, and magnetic saturation of a steel containing 0.93 per cent carbon and 2.03 per cent chromium, quenched from 1000°C. (1830°F.), specimen B_1 in water, B_2 in oil, and B_3 in oil followed by immersion in liquid air. (*Maurer and Schroeter.*[251])

chromium greatly reduced the critical cooling rate and that the effect per unit of chromium increased up to about 1 per cent chromium, after which chromium had a relatively smaller effect. The critical cooling rate was lowered somewhat with increasing carbon up to about 1 per cent carbon.

Wever and Jellinghaus pointed out that transformation took place in three temperature ranges: at the highest temperature, pearlite or sorbite (fine pearlite) was produced. At the inter-

mediate transformation, the structure was acicular (when formed at a relatively low temperature, it appeared somewhat like martensite but etched darkly; when formed at relatively high temperatures, it had the appearance of troostite resulting from tempered martensite). The lowest transformation, which occurred at temperatures from 400°C. (750°F.) to somewhat below 200°C. (390°F.), produced true martensite. X-ray examination by the Debye-Sherrer method showed that alpha iron was formed at the high temperature and had the same parameter as chromium-free ferrite within the limits of accuracy of their equipment. After transformation at the intermediate temperature, the parameter

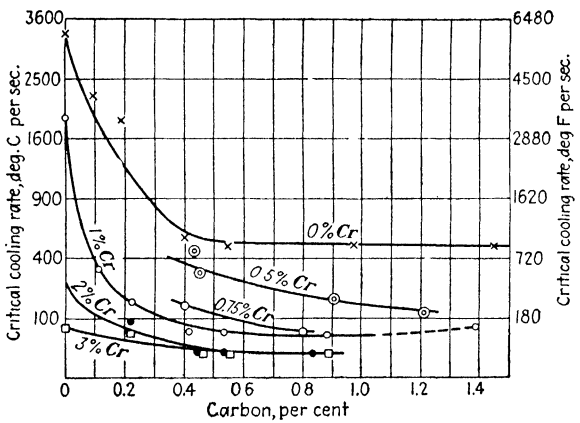


FIG. 66.—Effect of carbon and chromium on the critical cooling rate. (*Wever and Jellinghaus.*[378])

of the alpha iron was unchanged, indicating that it was not supersaturated with carbon. After the martensitic transformation a tetragonal phase was formed in which the axial ratio increased with carbon.

Esser, Eilender, and Majert[387] investigated a series of chromium steels by the method developed by Esser, Eilender, and Spenlé[275,358] in which thin disks 0.5 to 1 mm. in diameter, or spheres 1 to 2 mm. in diameter, are welded to thermocouple leads so as to form a hot junction of the elements. The sample is heated electrically in a vacuum and cooled by introduction of air or some other gas. They found that chromium tended to promote the formation of martensite, but its effect was less strong than that of manganese. They determined the cooling velocity

required to produce the first indication of martensite, and the velocity required to avoid completely the formation of pearlite. The results of their work are shown in Table 23.

TABLE 23.—CRITICAL AND SUBCRITICAL COOLING RATES OF CHROMIUM STEELS*

Specimen No.	Composition, per cent		Quenching temperature, °C.	Subcritical rate,† °C. per sec.	Critical rate,† °C. per sec.
	C	Cr			
21	0 55	0 56	950	75	400
22	0.48	1.11	950	20	100
23	0.52	1 96	950	11	22
24	0.38	2 64	950	4	10 to 15
25	0.36	16 20	1100	15	1500
26	1.09	0.53	1050	80	300
27	1 02	1 04	1050	21	100
28	0.92	2.00	1050	11	25
29	1 19	3 03	1050	11	20
30	1.33	0.48	1100	50	150
31	1.23	1.05	1100	20	85
32	1 33	1 87	1100	12	30
33	1 44	2.86	1100	12	25

* Esser, Eilender, and Majert [387]

† The subcritical rate is that which produces the first indication of martensite; the critical rate is that required to prevent completely the formation of pearlite.

62. Investigations of Bain and Coworkers on Transformation of Chromium Steels at Constant Temperatures.—Davenport and Bain[272] and Bain[354,413] have shown that in transformation at constant temperature, chromium slows up the inception of the transformation of austenite, as shown in Figs. 67 and 68. However, the transformation was found to proceed more rapidly at 715°C. (1320°F.) once it had started, as shown in Fig. 69. In cooling at given rates, chromium was found to lower the temperature of transformation and give a higher hardness. This is shown in Fig. 56, page 106. As shown in Fig. 70, a steel containing 1.0 per cent chromium hardened to a greater depth than a steel containing 0.74 per cent carbon when quenched under identical conditions. The chromium steel, however, was not so deep hardening as the chromium-nickel steel also shown in Fig. 70.* Work on practically carbon-free iron-chromium alloys

* The exact composition of the three steels was not given by Bain.

indicated that chromium conferred little strength on the ferrite and that it produced greater hardness in steel only by lowering the critical cooling rate. As shown in Fig. 71, chromium raised

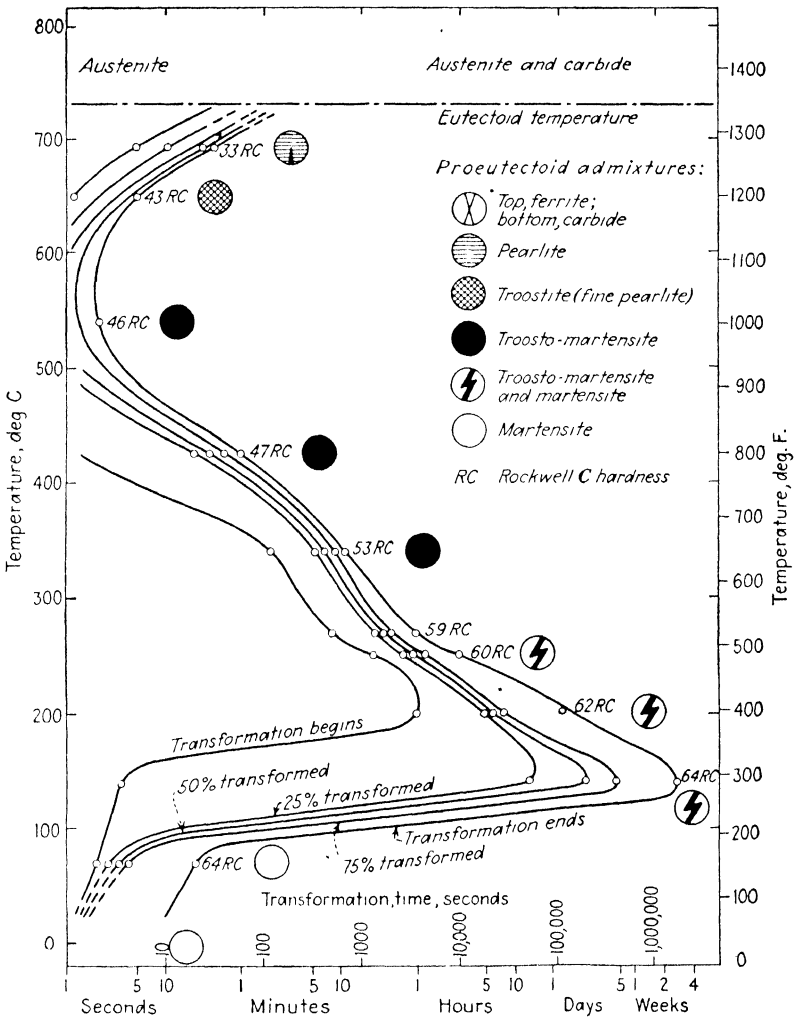


FIG. 67.—*S*-curves showing rate of transformation of austenite at constant temperature in steel containing 1.13 per cent carbon, 0.30 per cent manganese, and 0.171 per cent silicon. (*Davenport and Bain.*[272])

the temperature at which softening occurred on tempering; this was considered to result from the lower diffusion rate of chromium-bearing carbide.

63. Other Investigations on Transformation of Chromium Steels at Constant Temperatures.—In 1935, Tofaute, Sponheuer,

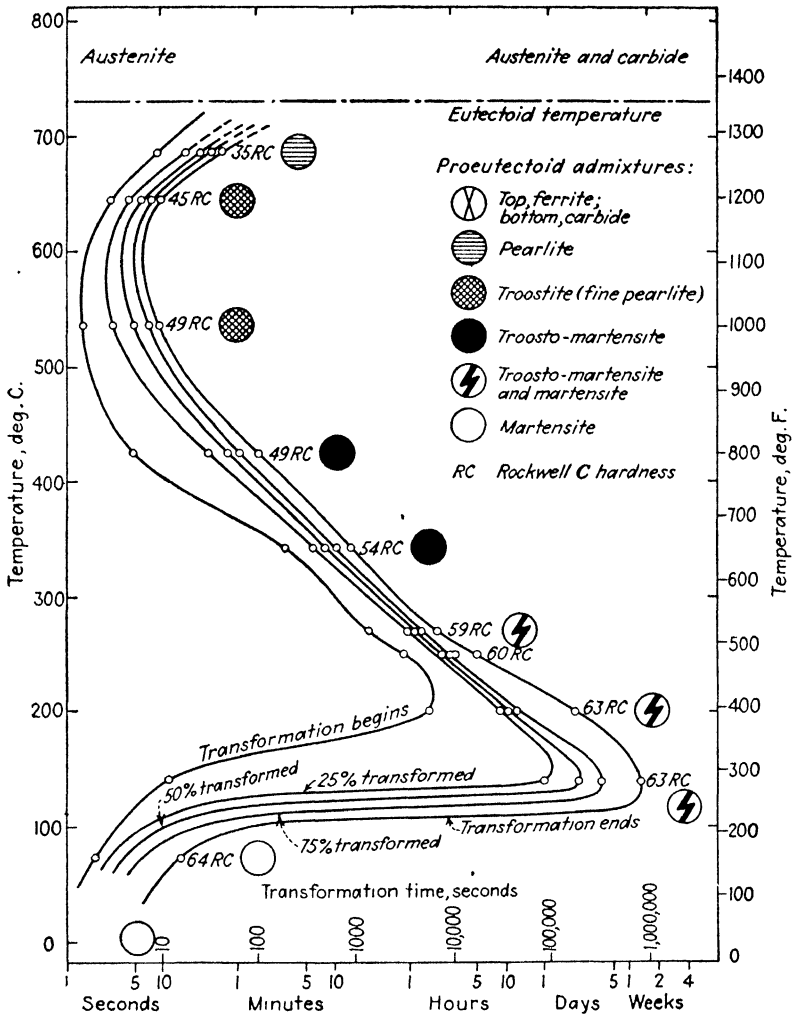


FIG. 68.—*S*-curves showing rate of transformation of austenite at constant temperature in steel containing 1.17 per cent carbon, 0.30 per cent manganese, 0.180 per cent silicon, and 0.26 per cent chromium. (*Davenport and Bain.*[272])

and Bennek[439] quenched specimens, 60 mm. (2.36 in.) in diameter by 120 mm. (4.62 in.), of steels containing 1.6 and 3 per cent chromium with 0.4 and 1.0 per cent carbon in water after 2 hr.

at 900 to 950°C. (1650 to 1740°F.). The steels failed to harden throughout so a new series was tested in the same section. Quenching temperatures below 900°C. (1650°F.) failed to harden satisfactorily, and over 900°C. an overheated grain condition was found. The compositions and results shown in Table 24

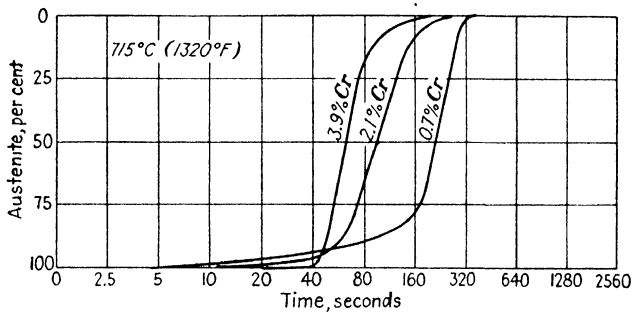


FIG. 69.—Rate of transformation of austenite at 715°C. (1320°F.) in three 0.55 per cent carbon steels of indicated chromium content. (*Bain.*[354])

and in Fig. 72 indicate that in the section tested only the 0.4 per cent carbon 2 per cent chromium steel, and the 3 per cent chromium steels in both 0.4 and 1.0 per cent carbon ranges were hardened throughout. It was concluded that the presence of the trigonal carbide $(Cr,Fe)_7C_3$ was essential for deep hardening and

TABLE 24.—COMPOSITION OF STEELS USED FOR DEEP-HARDENING INVESTIGATION*

Steel	Composition, per cent			
	C	Cr	Mn	Si
1	0 40	0 00	0 45	0 40
2	0.40	0 53	0 43	0 39
3	0 42	1 00	0.46	0.41
4	0 41	1 57	0.50	0.46
5	0 42	2.02	0 45	0.44
6	0.39	3 11	0.47	0.52
11	0.87	0 00	0.41	0.17
12	0.95	0.47	0.49	0.45
13	0.96	0.99	0.50	0.44
14	1.02	1 64	0.50	0.44
15	0.97	2.00	0 50	0.46
16	1.00	3 12	0 55	0 55

* Tofaute, Sponheuer, and Bennek.[439]

that lower chromium steels behaved fundamentally like unalloyed steel.

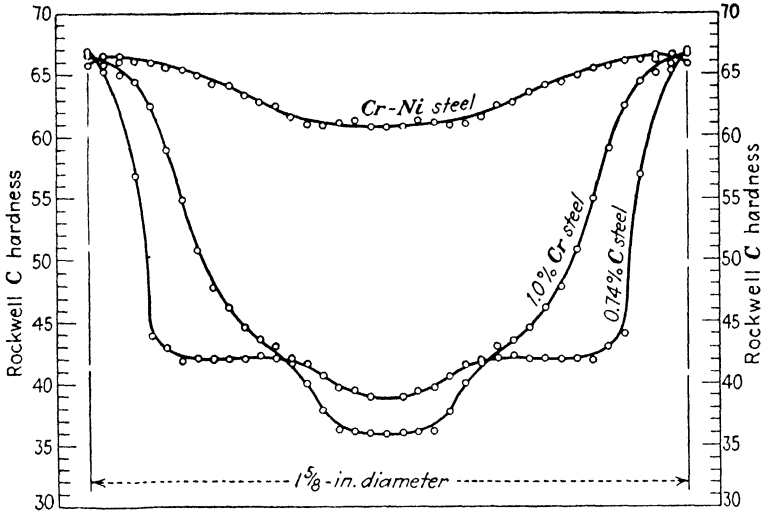


FIG. 70.—Effect of carbon, chromium, and chromium plus nickel on deep hardening of steels. Composition of steels not given. (*Bain* [413])

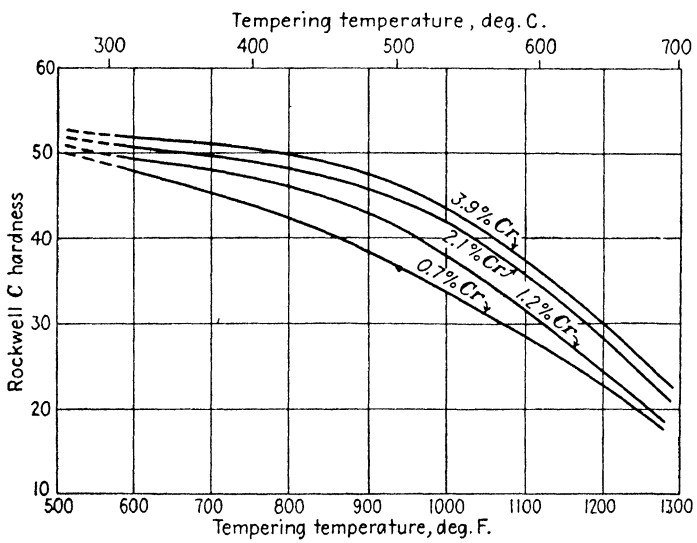


FIG. 71.—Effect of tempering temperature (1 hr.) upon the hardness of quenched 0.55 per cent carbon steels of indicated chromium content. (*Bain.*[413])

After quenching and tempering at various temperatures, chromium was found to promote retention of hardness up to 500°C.

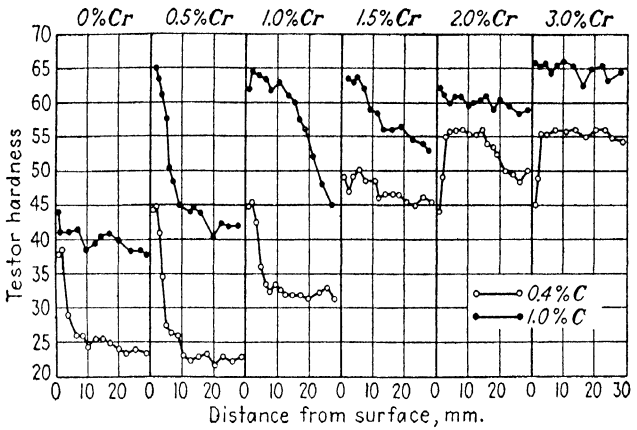


FIG. 72.—Deep hardening of low-chromium steels. "Testor" values are to Rockwell *C* hardness as 10 is to 9. (*Tofaute, Sponheuer, and Bennek.*[439])

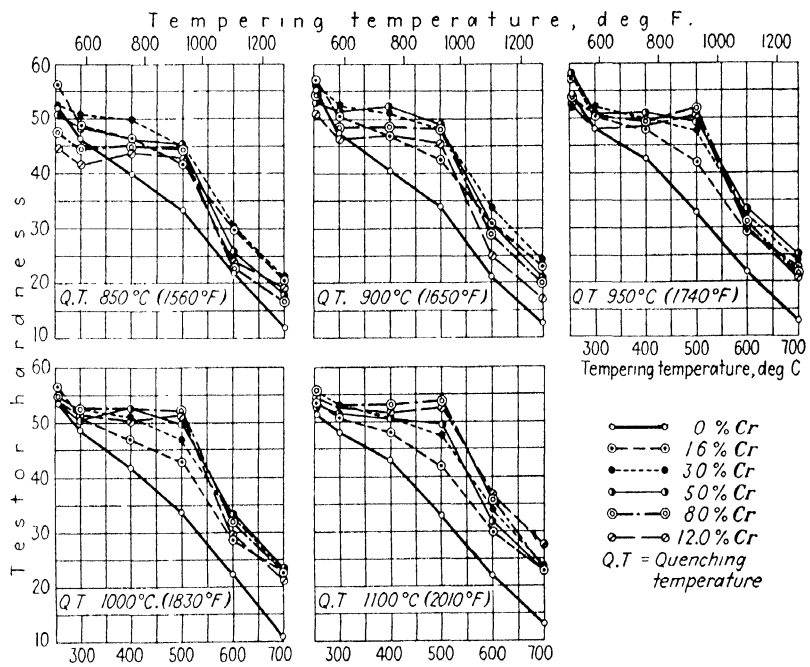


FIG. 73.—Effect of carbon and chromium on the retention of hardness upon tempering quenched low-chromium 0.4 per cent carbon steels. (*Tofaute, Sponheuer, and Bennek.*[439])

(930°F.), as shown in Figs. 73 and 74. It will be noted that very nearly maximum hardness was obtained with 3 per cent chromium.

Döpfer and Wiester[416] measured the transformation at constant temperature magnetically, according to the method of

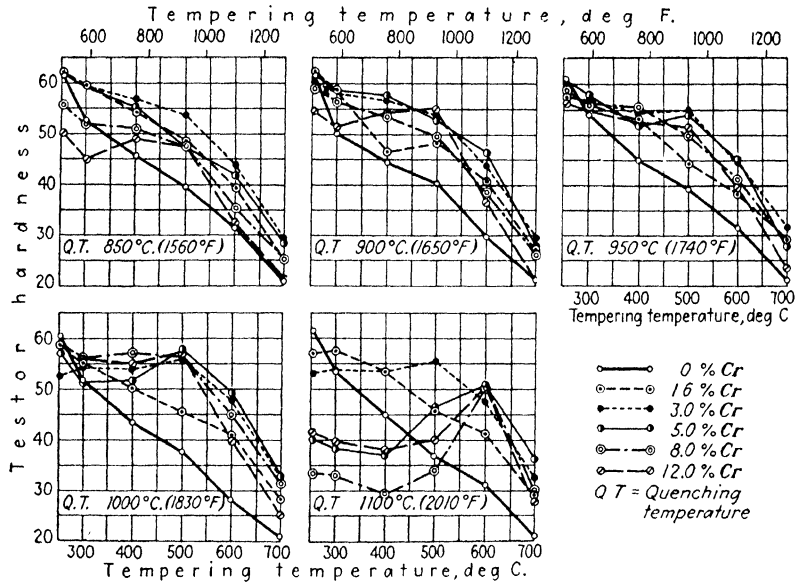


FIG. 74.—Effect of carbon and chromium on the retention of hardness upon tempering quenched low-chromium 1.0 per cent carbon steels. (*Tofaute, Sponheuer, and Bennek.*[439])

Schottky (described in the discussion of an article by Wever[349]), on specimens of 2 and 3 per cent chromium steels with the following analyses:

Steel	Composition, per cent			
	C	Cr	Mn	Si
60 Cr 2	0 54	1.85	0 45	0 29
40 Cr 3	0 40	3.10	0.47	0 52
70 Cr 3	0 72	3.18	0 52	0 53
100 Cr 3	1 00	3 18	0.55	0 55

Specimens of these steels were heated at 850°C. (1560°F.) for 10 min. and quenched in a salt bath held at the desired tem-

perature. The time required for the transformation to start is shown in Table 25. Figure 75 shows the rate of transformation

TABLE 25.—TIME REQUIRED TO START TRANSFORMATION OF FOUR LOW-CHROMIUM STEELS AT VARIOUS TEMPERATURES*

Temperature		Time for beginning of transformation, sec.			
°C.	°F.	60 Cr 2	40 Cr 3	70 Cr 3	100 Cr 3
150	300	0	0	0	0
175	345	0	0	0	8400
200	390	0	0	0	7600
225	435	0	0	3000	
250	480	0	0		2400
275	525	65	0	2580	
300	570	55	5	630	5900
325	615	20	65		
350	660	40	60		720
375	705	40	75		
400	750	15	<10000	240	<10000
425	795	25	<10000	<10000	<10000
450	840	43	<10000	<10000	<10000
500	930	20	<10000	<10000	<10000
550	1020	270		1800	4000
600	1110	70	90	300	0

* Dopfer and Wiester [4.6]

of 0.6 per cent carbon steels containing 2 per cent of chromium, molybdenum, or vanadium. No conclusions were drawn from the total time required for transformation on account of questionable end points. It will be noted that three ranges of austenite instability were found corresponding to the pearlite, cubic or pseudo martensite, and tetragonal martensite. The maximum rate of transformation, after it once started, was found at 350 to 400°C. (660 to 750°F.), and a secondary maximum was found at 275 to 300°C. (520 to 570°F.). It was observed that higher carbon increased the time required to start transformation.

64. Summary of Critical Temperatures of Low-chromium Steels and the Effect of Manganese.—It is apparent from the foregoing that only a broad generalization on the effect of chromium on the austenite transformation is possible. The primary investigations on steels containing up to 3 5 per cent chromium were those by Edwards, Sutton, and Oishi; Murakami; Wever and

Jellinghaus; Esser, Eilender, and Majert; and Döpfer and Wiester. While these investigators have covered a fairly broad range of compositions with respect to carbon and chromium, there is very little agreement among their results. Edwards, Sutton, and Oishi and Murakami agree fairly well on the effect of initial temperature and cooling rate. In the same ranges, Wever and Jellinghaus and Esser, Eilender, and Majert show much higher critical cooling rates. This may be due to their methods, which were different, the former investigators using relatively large

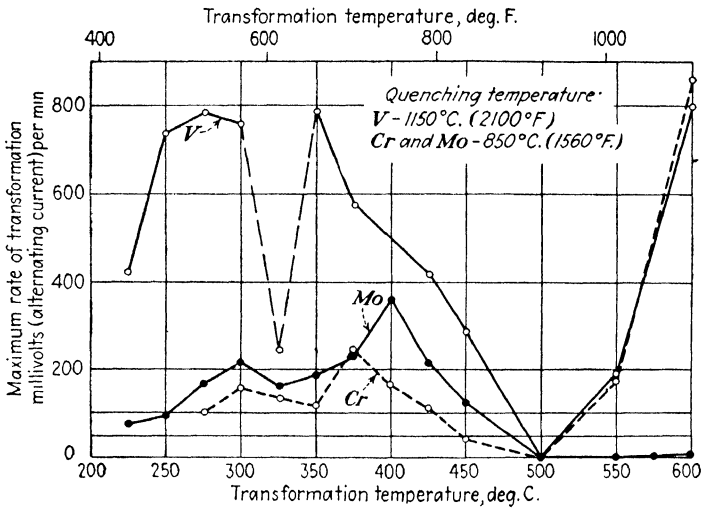


FIG. 75.—The effect of 2 per cent chromium, molybdenum, or vanadium on the rate of transformation of 0.6 per cent carbon steels at various temperatures (*Döpfer and Wiester.*[416])

samples and more conventional equipment which gave critical cooling rates that were much lower than those of the others. The effect of mass alone may have some bearing on this lack of agreement. However, it will be noted that Edwards' and Murakami's steels contained on the order of 0.20 to 0.30 per cent manganese, whereas Wever and Jellinghaus' steels contained usually less than 0.10 per cent manganese and those of Esser, Eilender, and Majert, an unknown amount.

Work carried out at the Union Carbide and Carbon Research Laboratories, Inc., on the effect of manganese on the critical cooling rate of steels containing up to 4 per cent chromium has indicated that manganese is one of the major controlling factors.

Critical temperatures were measured dilatometrically on 0.35 per cent carbon-steel samples cooled at the rate of 2.3°C. per sec. at 800°C. (1470°F.) after heating to 925 to 950°C. (1700 to 1740°F.). Results are shown in Table 26 and in Fig. 76. It will be seen that manganese contents of 0.2 per cent or less have a very pronounced effect on the critical cooling rates of 2 and 3 per cent chromium steels, and this effect is sufficiently great to account for some of the inconsistencies noted above. Other factors, such as the effect of previous treatment, grain size, and effect of mass, have received no consideration, and the critical velocities required completely to effect the transformation to martensite have been

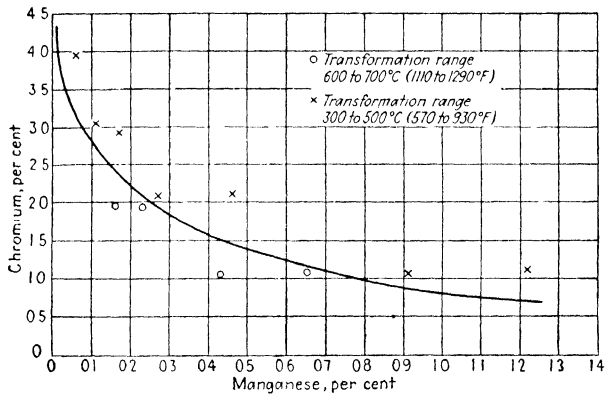


FIG. 76.—Effect of manganese on the transformation of chromium steels containing 0.35 per cent carbon, cooled at 2.3°C (4.14°F) per sec. from 925 to 950°C. (1700 to 1740°F.) (*Union Carbide and Carbon Research Laboratories, Inc.*)

considered very little except by Esser, Eilender, and Majert, and by Tofaute, Sponheuer, and Bennek. For these reasons it is not possible to define specifically the conditions necessary to produce a given structure in a given steel.

Studies of transformation at constant temperature have been carried out by Bain and coworkers and by Döpfer and Wiester on steels of a limited range of compositions. While their work has indicated a more rational explanation of phenomena such as depth hardening, and should lead to more effectively balanced alloy steels, a quantitative evaluation of the effect of chromium on austenite transformation cannot yet be made.

The effect of chromium on the transformation of austenite and the resulting structures may be summarized as follows:

1. Low-chromium steel behaves similarly to carbon steel except that the transformation of austenite is rendered more sluggish so that, in cooling at a constant rate, higher chromium steels transform at lower temperatures.

2. At low rates of cooling, pearlite is formed by transformation in the range of 600 to 700°C. (1110 to 1290°F.). The temperature of the transformation is lowered by increase in rate of cooling until no transformation occurs in this range.

3. At higher rates of cooling, transformation is discontinuously depressed to a range of 500 to 300°C. (930 to 570°F.) where a structure having the appearance and characteristics of tempered martensite is formed The hardness abruptly increases with depression of the transformation.

TABLE 26.—TRANSFORMATION TEMPERATURES OF STEEL HEATED TO 925 TO 950°C. AND COOLED AT 2.3°C. PER SEC.*

Heat	Composition, per cent				Arrest on cooling, °C.
	C	Cr	Mn	Si	
1228	0 42	1 03	0 43	0 19	654
1200	0 37	1.07	0.65	0 40	630
1202	0 33	1 06	0 91	0 26	540
1204	0 35	1.11	1.22	0 26	480
3520	0 36	1 95	0 16	0 31	656
3521	0 34	1 93	0 23	0 27	661
1916	0 35	2.09	0 27	0 25	473
1920	0 34	2 11	0 46	0 25	485
3522	0 34	3.03	0 11	0 27	432
3523	0.33	2 92	0 17	0 25	442
3524	9 35	3 93	0 06	0 28	453

* Union Carbide and Carbon Research Laboratories, Inc.

4. At still higher cooling rates, transformation occurs in a still lower range of temperatures with the formation of true martensite having a tetragonal atomic lattice.

5. With certain fast rates of cooling, high-carbon chromium steels tend to retain a moderate amount of austenite.

6. On reheating, martensite is decomposed in the neighborhood of 150°C. (300°F.), and austenite is transformed at temperatures above 300°C. (570°F.).

7. Owing to the sluggish diffusion of chromium-bearing carbide, chromium causes a greater retention of hardness on tempering

8. Higher initial temperature causes a reduction in the critical hardening rate and may be due to solution or dissociation of chromium-bearing carbide, or to other factors such as grain growth.

9. While trigonal carbide, $(Fe,Cr)_7C_3$, has been definitely identified in steels containing over 2 per cent chromium, specific effects that have been ascribed to its influence have not as yet been well substantiated.

10. Chromium increases the time necessary for transformation at constant temperature, and the effect is most pronounced when the rate of cooling necessitates transformation at relatively low temperature.

65. Carburizing.—The effect of chromium on the depth of penetration of carbon in case carburizing was observed at an early date. Guillet[30] reported that chromium materially increased the depth of carburizing. This was confirmed by Giesen[44] who carburized a series of chromium steels under various conditions with the following results:

Chromium content of steel, per cent	None	1 5	2.0	2 5	3 0
Thickness of carburized layer, mm	0 89	1 12	1 14	1 27	1 31

Similar results have been reported by Lothrop,[54] Gebert,[78] Spalding,[114] and Brearley.[95] Oertel[205] found that the surface hardness was increased by chromium. Scherer,[400] in studying cyaniding, found similar results from the addition of chromium. Chromium tended to concentrate carbon at the surface, and the properties were almost entirely dependent on the surface layer rather than on the characteristics of the core. Houdremont and Schrader[425] studied the effect of time and temperature on the carbon content of the case, the depth of case, and the grain size of steels containing 0, 1.5, and 3.0 per cent chromium. Their results, shown in Figs. 77 and 78, indicated that chromium steels were sensitive to overheating so that grain growth occurred, and that there was a tendency for the carbides to form in the austenite boundaries when the case was very high in carbon.

Chromium appears to have a very slight tendency to make steel coarse grained, as shown by the McQuaid-Ehn test, but this tendency is not so strong as in the case of manganese. The tendency becomes apparent only in steel containing about 3 per cent chromium, and under extreme conditions it results in the intergranular carbide reported by Houdremont and Schrader. When the higher chromium steels have been treated with a grain-refining addition, small carbides are formed throughout the grains. Ehn[105] reported after the examination of many steels that chromium has a strong tendency toward making steel "normal," *i.e.*, causing minimized pearlite divorce. On account of the resulting uniformity of hardening characteristics, improvement in machinability, and increased rate of carburizing, he

recommended the addition of 0.30 to 0.50 per cent chromium to 0.20 per cent carbon carburizing steel.

M. J. R. Morris, in a private communication, pointed out that chromium results in an abnormal marginal layer on carburizing

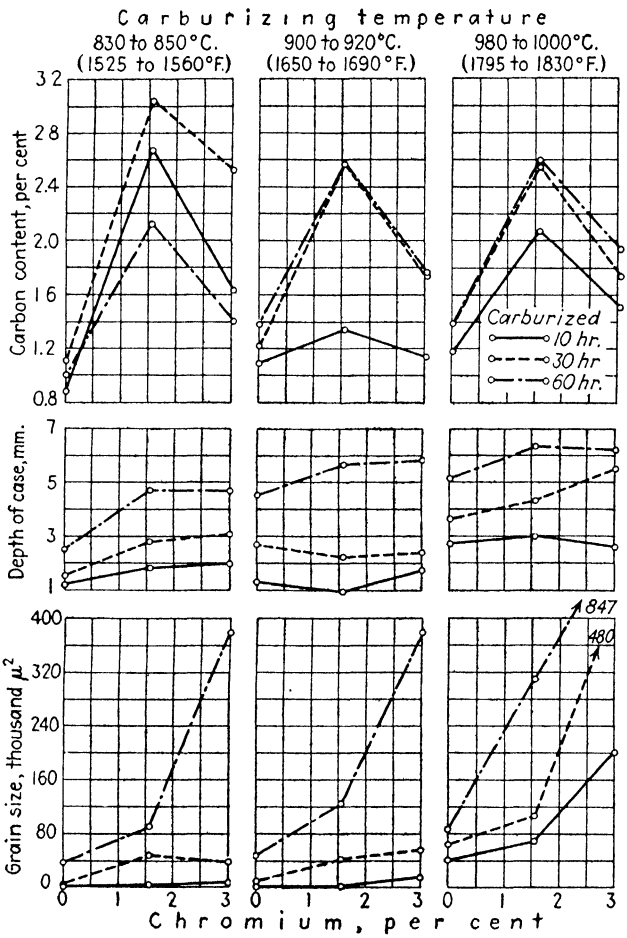


FIG. 77.—Effect of temperature and time on carburizing of low-chromium steels. (*Houdremont and Schrader.*[425])

and further results in a very high carbon concentration when the material is subjected to gas carburizing at relatively low temperatures.

66. Decarburizing and Scaling.—Although it has long been recognized that chromium reduces decarburizing and scaling,

relatively little work has been carried out on the lower chromium steels. Exposure at high temperatures produces a fairly close scale in chromium steels and, although the scale is more adherent than in plain carbon steel, it flakes off readily during rolling.

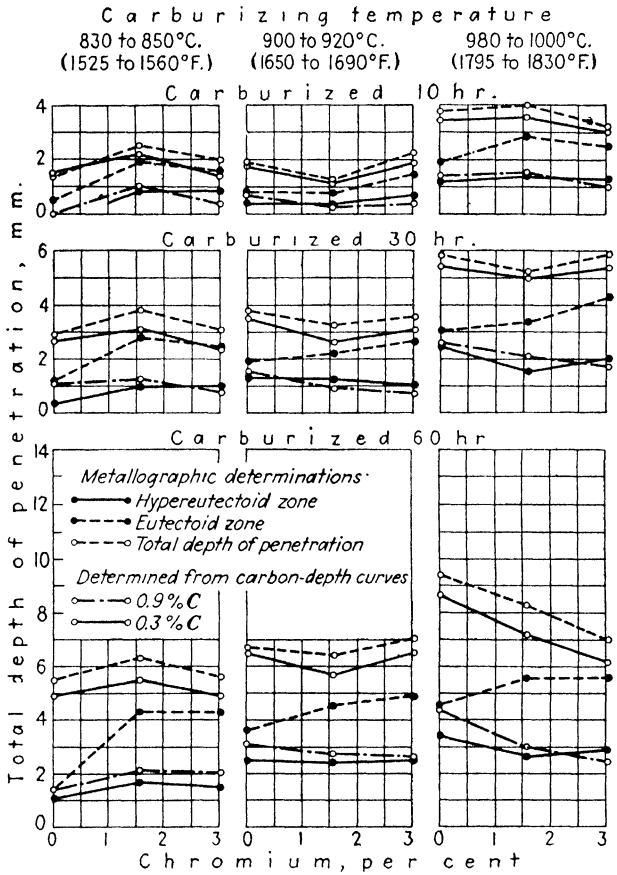


FIG. 78.—Effect of temperature and time on carburizing of low-chromium steels. (*Houdremont and Schrader* [425])

The penetration of oxide into the metal and decarburization are reduced somewhat, the degree of oxidation decreasing with increase in the chromium content. This is shown by Schrader[434] in Figs. 79 and 80. Pfeil[254] examined the scale of chromium-bearing steels and found a concentration of chromium oxide in the innermost layer. In lower temperature ranges decarburiza-

tion is somewhat reduced by chromium, but the degree of difference is relatively small. In line with the concept that scaling and decarburizing tendencies are in opposition, it has been found that under oxidizing conditions chromium-bearing spring steel decarburized less than carbon and silicon steels, and in tool steels the effect of chromium is noticeable in the amount of grinding required after hardening. The effect of chromium on decarburization in hydrogen has been studied by Campbell, Ross, and Fink[119,120] and by Austin.[412] They found that chromium steels decarburized less readily and that resistance to decarburization increased continuously with increase of chromium content.

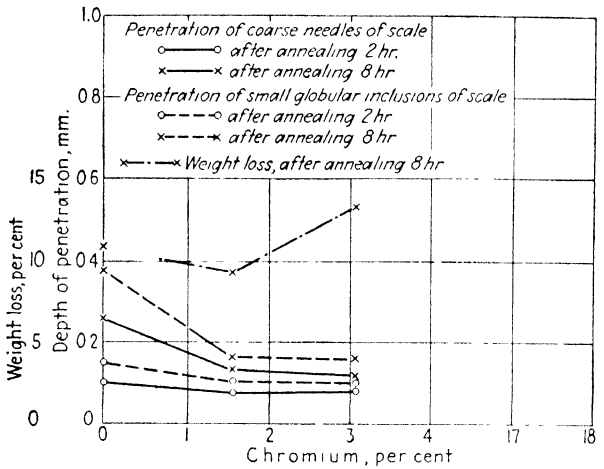


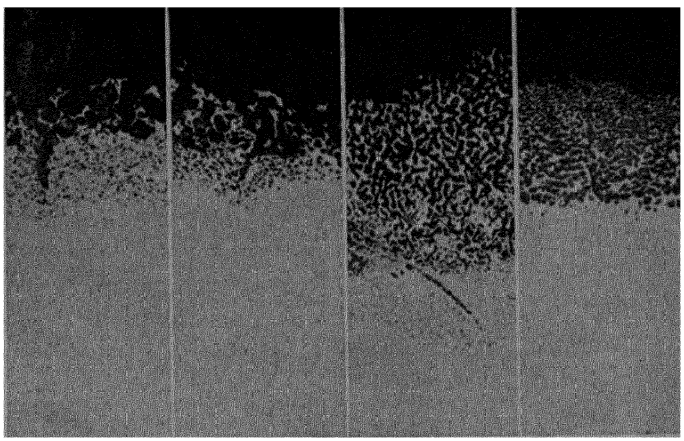
FIG. 79.—Effect of chromium on penetration of scale into steel. (*Schrader.*[434])

D. AUTHORS' SUMMARY

1. Plain low-chromium steels containing up to 3.5 per cent chromium represent an appreciable portion of the total of low-alloy steels produced today. The chromium is invariably introduced at the end of the heats in the form of ferrochromium of appropriate carbon content. Production in the mill requires very little extra precaution other than that common to alloy-steel practice, which involves thorough deoxidation on melting, careful mold practice and cropping of ingots, and greater care in deseaming and in hot- and cold-working operations.

2. Welding of these steels requires no special precautions, although the tendency to air harden must be given particular

attention when the carbon or the chromium content is in the upper bracket of the range in question; and the tendency to pick up carbon under reducing conditions must be considered. Oxy-acetylene cutting presents no undue difficulties, as the nature of the oxide is not changed to an appreciable degree with small quantities of chromium. Again, however, the tendency to air hardening is to be reckoned with in the high chromium and carbon ranges.



1.56 % Cr | 3.02 % Cr | 1.57 % Cr, 4.16 % Ni | 17.8 % Cr, 9.0 % Ni

FIG. 80.—Scaling of chromium and chromium alloy steels. 75×. (*Schrader.*[434])

3. Machinability of the chromium steels is in general equivalent to that of carbon steels with like physical properties. In this connection the relative ease of annealing is worthy of special mention.

4. The low-chromium steels are particularly responsive to heat treatment. For a given carbon content the critical point on heating is raised slightly by the chromium, and on cooling it is markedly depressed at higher cooling rates. At any given temperature at which gamma-alpha transformation is possible, the rate of transformation is decreased by the presence of chromium. In this way it overcomes mass effect to a great degree and eliminates the necessity for an extremely drastic quench for the desired structure.

5. The effect of small amounts of elements other than carbon on the reactions mainly due to chromium may be very marked. This is notably true in the case of manganese, and the failure of earlier investigators to give due importance to variations in the small amount of ever-present manganese probably accounts for many of the reported inconsistencies.

6. Cooling from increasing temperatures above the transformation temperature on heating has little effect, but there is a slight tendency to reduced sluggishness as the temperature of heating is increased. As the chromium content increases in the range in question, transformation from the austenitic to the ferritic state becomes more sluggish and pearlite is formed at low rates of cooling with transformation at some 650°C. (1200°F.). With higher rates of cooling, the transformation temperature is markedly depressed and self-tempered martensite occurs with transformation at approximately 400°C. (750°F.). At still higher cooling rates, true martensite is formed at transformation temperatures below 300°C. (570°F.). At these higher cooling rates, the higher carbon chromium steels retain a moderate amount of austenite and this is not decomposed on tempering at temperatures below 300°C. (570°F.). As in certain other steels, a greater proportion of austenite is retained by oil quenching than by water quenching. Martensite in chromium steels starts to decompose at 150°C. (300°F.), but higher temperatures are necessary to reduce the hardness appreciably.

7. Chromium steels may be readily carburized or cyanided; the chromium materially increases the depth of case resulting from a given carburizing treatment, with simultaneously increased surface hardness. In addition, chromium tends to prevent pearlite divorce. As would be expected, decarburization is reduced by chromium in the steel, particularly under oxidizing conditions. This is accompanied by reduced scaling and a more adherent, uniform scale.

CHAPTER VII

PROPERTIES OF PLAIN LOW-CHROMIUM ENGINEERING STEELS

Tensile and Impact Properties—Effect of Mass on Tensile and Impact Properties—Miscellaneous Mechanical Properties—Effect of Low and High Temperatures—Mechanical Properties of Low-chromium Cast Steels—Miscellaneous Properties—Industrial Application—Authors' Summary

Information on the properties of chromium steels was extremely limited until Hadfield[19] in 1892 reported his investigation on the effect of chromium on mechanical properties and corrosion resistance. This was followed by the well-known memoir of Guillet on alloy steels, published in 1904 and 1905.[31,36] Since 1910, a large amount of work on plain low-chromium steels has been reported, chiefly on tensile and impact properties and to a lesser extent on resistance to torsion and fatigue and on the effect of low and high temperatures on mechanical properties. This information is summarized in the present chapter.

A. TENSILE AND IMPACT PROPERTIES

The few data on the mechanical properties of low-chromium steels reported before 1890, which are adequately summarized in Howe's[18] book on "The Metallurgy of Steel," published in 1891, are only of historical interest. Since the papers by Hadfield[19] and Guillet,[31,36] a large number of investigators have studied and reported the mechanical properties of steel containing up to 3.5 per cent chromium; some of these reports[51,73,90,116,407] include data on the effects of higher chromium contents. As the values reported in these investigations usually represent only one or two conditions of heat treatment a concise correlation is difficult. As an aid in the present correlation, the data have been assembled according to chromium content and further subdivided according to heat treatment as follows: (*a*) forged or rolled;

(*b*) annealed;* (*c*) normalized; (*d*) oil quenched; and (*e*) water quenched. Details of manufacture have not been included. For all data, the specimens treated or tested were approximately 1 in. in diameter or somewhat less except in the work of Dickenson,[73] who used 2-in. square bars. The data have been tabulated (Tables 27 to 51 inclusive) according to investigators rather than by chemical analysis.

TABLE 27.—MECHANICAL PROPERTIES OF FORGED STEELS CONTAINING 0 TO 0.75 PER CENT CHROMIUM

Investigator	Composition, per cent				Tensile strength, lb./sq in	Yield strength, lb./sq in	Elongation,* per cent	Reduction of area, per cent	Brinell hardness	Impact value,† m-kg
	C	Cr	Mn	Si						
Hadfield[19]	0 07	0 22	0 11	0 07	43,700	62,700	38 6	64 1		
	0 16	0 29	0 18	0 07	47,000	62,700	42 0	67 1		
	0 15	0 48	0 21	0 10	50,400	69,400	37 7	43 9		
	0 14	0 57	0 25	0 08	47,000	65,000	41 0	68 5		
Guillet[81]	0 04	0 70	Trace	0 97	32,100	50,200	25 0	74 9	95	32
	0 86	0 52	0 03	0 24	112,300	155,000	2 5	16 6	310	3

* Gage length not given.

† Frémont specimen, dimensions not given.

Unless otherwise noted, the tensile data reported in this and subsequent chapters were obtained from U. S. standard 0.505-in. or British standard 0.564-in. round specimens. The value reported as yield strength is, unless otherwise stated, the yield point by dividers or drop of beam, or the load for an extension of 0.2 per cent.

67. Steels Containing 0 to 0.75 Per Cent Chromium.—Chromium in this range (Tables 27 to 29) has little effect on normalized steels if the carbon is low, and has only a moderate effect on more rapidly cooled steels containing either high or low carbon. If high-carbon steels are to be rapidly cooled, the addition of chromium raises the hardening capacity and retards the softening

* The terms annealing or annealed are used in this monograph in their usual sense; namely, heating or heated above the critical range followed by slow cooling through the range. This corresponds to "full annealing" as defined in "Metals Handbook,"[463] p. 211 When any other annealing treatment is meant the meaning of annealing or annealed will be clear from its use in the text.

caused by tempering but only to a rather small degree. This is confirmed by commercial experience where the plain 0.5 per cent chromium grade is used only in carburizing steels and in tool steels where a moderately increased uniformity and depth of hardening are required.

TABLE 28.—MECHANICAL PROPERTIES OF ANNEALED OR NORMALIZED STEELS CONTAINING 0 TO 0.75 PER CENT CHROMIUM

Investigator	Composition, per cent				Annealing or normalizing temperature		Tensile strength, lb/sq in	Yield strength, lb/sq in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness	Izod impact, ft-lb.
	C	Cr	Mn	Si	°C	°F.						
Annealed												
Hadfield[19]	0 07	0 22	0 11	0 07			53,700	36,900	45 2	68 2		
	0 16	0 29	0 18	0 07			56,000	38,100	45 5	65 9		
	0 15	0 48	0 21	0 10			61,600	40,300	44 9	62 0		
	0 14	0 57	0 25	0 08			57,200	33,600	46 6	69 0		
Arnold and Read[51]	0 64	0 65					96,700	45,900	24 5*	40 5		
Moore[90]	0 36	0 25	0 34	0 15	930	1705	74,200	40,700	31 0	47 3		
	0 36	0 25	0 34	0 15	1070	1960	73,500	45,200	34 0	51 1	123	6 9†
	0 36	0 52	0 32	0 19	930	1705	79,600	47,500	32 0	51 1		
	0 36	0 52	0 32	0 19	1070	1960	77,400	45,100	31 0	51 1	133	5 3†
Jones[285]	0 31	0 66	0 46				75,500	41,200	34 0	57 0	142	46 0
	0 30	0 38	0 89				76,800	47,100	34 0	62 0	145	56 0
	0 31	0 68	1 09				86,600	51,500	32 0	58 0	168	49 0
Normalized												
Jones[285]	0 31	0 66	0 46		830	1525	77,500	47,500	36 0	65 0	152	66 0
	0 30	0 38	0 89		860	1580	81,300	51,100	35 0	65 0	159	57 0
	0 31	0 68	1 09		860	1580	93,000	59,600	30 0	63 0	187	53 0

* Gage length not given

† Guillery, m-kg per sq cm Specimens 56 by 10 by 10 mm, notch 1 mm radius, 2 mm deep by 2 mm. wide, striking energy of 60 m-kg, velocity 8 8 m per sec, supported on 40-mm span

McQuaid, in commenting* on the first draft of this chapter, wrote:

As a matter of fact, the addition of small amounts of chromium has a very important place in the production of commercial steels. A com-

* Private communication, Dec. 23, 1936.

TABLE 29.—MECHANICAL PROPERTIES OF OIL-QUENCHED OR WATER-QUENCHED AND TEMPERED STEELS CONTAINING 0 TO 0.75 PER CENT CHROMIUM

Investigator	Composition, per cent				Quenching temperature		Tempering			Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness	Izod impact, ft-lb.
							Temperature		Time, hr.	Cooled in						
	C	Cr	Mn	Si	°C.	°F	°C.	°F.								
Oil quenched																
Moore[90]	0 36	0 25	0 34	0 15	860	1580	695	1285	1	Air	82,900	51,700	35	67 8	143	19 9*
							600	1110	1	Air	91,900	67,800	31	63 7	161	16 5*
	0 36	0 52	0 32	0 19	860	1580	695	1285	1	Air	89,600	60 400	33	64 8	165	15 4*
							600	1110	1	Air	95,400	64 500	28	60 5	178	12.9*
	0 36	0.25	0 34	0 15	855	1570	735	1355	2⅓	Air	77,700	44,700	37	67 8	139	18 8*
							555	1030	⅓	Water	96,500	71,700	28	57 1	184	9 4*
	0 36	0 52	0 32	0 19	855	1570	735	1355	2⅓	Air	83,900	59,500	34	64 8	152	15 6*
							555	1030	⅓	Water	98,700	70,800	27	57.1	194	9 6*
Jones[98]	0 37	0 75	0 22	0 13	1000	1830	650	1200	2	Water	94,700	61,100	28	67 0	198	46 0
									2	Furnace	91,000	59,400	28	67 0	192	40 0
					900	1650	650	1200	1	Air	95,000	64,300	27	69 0	193	53.0
									2	Water	91,200	60,000	30	70 0	194	53 0
									2	Furnace	90,300	60,000	30	70 0	192	49 0
									6	Air	88,900	59,100	31	71 0	185	60 0
							600	1110	1	Air	99,200	69,200	26	63 0	207	42 0
									2	Air	96,300	64,300	27	65 0	199	40 0
									6	Air	95 000	63,400	28	65 0	194	48 0
							550	1020	2	Air	102 000	71,500	24	59 0	215	34.0
							500	930	6	Air	102 200	70,400	23	59 0	216	28.0

								820	1510	650	1200	2	Air	90,500	58,900	31	70.0	185	48 0
										600	1110	2	Air	95,000	59,800	28	65 0	193	41.0
										550	1020	2	Air	100,600	66,100	25	62 0	210	31.0
Hankins and Ford[244]	0	60	0.56	0	62	0	26	800	1470	400	750			238,300	170,200†	2 5‡	2 0	469	2.0
										500	930			200,900	152,300†	5 6‡	11 0	413	9.0
										600	1110			164,000	100,800†	6 6‡	30 0	339	22 5
Bullens[71]	0	36	0	57	0	44	0	05	815	1500	650	1200			103,200	76,000§	27 0	62 0		
											705	1300			99,500	71,200§	22 0	51.4		
											705	1300			94,100	67,500§	28 0	69 0		
	0	70	0	50	0	60			760	1400	480	900			199,500	179,100§	6 0	25 6		
											540	1000			168 900	143,500§	12 5	33 8		
											595	1100			145 700	119,400§	15 0	42 2		
											650	1200			120,000	105,000§	17 0	47 5		
											705	1300			107 100	91,400§	22 0	58 1		
Abram[411]	0	30	0	66	0	14			925	1695	500	930	1	Water	86 900	58,200	24 0	57 0	...	37 0
											550	1020	1	Water	84 500	58,200	29 0	61 0		36 0
											600	1110	1	Water	84,700	53,400	32 0	63 0		43 0
											650	1200	1	Water	80,200	47,900	33 0	64 0		41 0
											700	1290	1	Water	76 200	48,800	37 0	70 0	.	57 0
Water quenched																				
Bullens[71]	0	47	0	51	0	60	0	11	795	1460	540	1000			168,400	153,700§	19 0	52 6	311	
											595	1100			143,100	128,900§	19 0	60 2	277	
											650	1200			112,900	120,800§	22 0	60 5	262	
											705	1300			120,600	109,500§	25 0	67 6	212	

* Guillery, m-kg. per sq. cm. See footnote †, Table 28.
† Reported as proportional limit
‡ Elongation in 8 in.
§ Reported as elastic limit.

bination of 0.70 to 1 per cent manganese and approximately 0.25 per cent chromium is an important factor in the production of an oil-quenching steel . . . for applications where it is necessary to avoid warpage and where in the interest of economy it is not advisable to use a more highly alloyed steel. Tests made have indicated that in flat spring sections containing 0.80 per cent carbon, 0.80 per cent manganese, and 0.25 per cent chromium, it was possible to obtain a Rockwell hardness of more than 60 after oil quenching. This can be obtained even in the fine-grained type of steel, and indications are that in this particular grade the chromium addition is more important than is grain size in the improvement of hardenability.

The introduction of 0.25 per cent chromium is important in obtaining high hardness with steels of the medium-carbon group. These steels have been used in large quantities in some crankshaft and tractor applications.

In the carburizing grade the addition of 0.25 per cent minimum chromium has been found to be a very important factor in the successful oil quenching of parts where warpage is important and where water quenching would otherwise be necessary.

Thus the combination of higher manganese limits with grain-size control has greatly increased the importance of a small chromium addition, and the indications are that small chromium additions will play a very important part in the development of lower alloy grades of steel as well as in the development of oil hardening of so-called plain carbon grade.

68. Steels Containing 0.75 to 1.5 Per Cent Chromium.—The increase of chromium to 1 per cent produces an increase of strength in all except the lowest carbon ranges, as shown in Tables 30 to 33. In the hot-worked condition this amount of chromium causes an increase in strength of 5000 to 10,000 lb. per sq. in., and so long as the strength does not exceed 120,000 lb. per sq. in. in 1-in. diameter sections, or 90,000 lb. per sq. in. in 3-in. diameter sections, the ductility is high enough to justify use of the steel in this condition. These properties have been utilized to a limited degree in some applications. Annealing effectively softens 1 per cent chromium steel, the actual hardness being determined primarily by the carbon content. After normalizing, the ductility and impact strength are improved as compared with rolled material, but the same limitation with respect to strength, ductility, and section size applies. A practical limit for tensile strength in sections up to 1.5 in. in diameter is 100,000 lb. per

sq. in. This may be obtained with 0.35 per cent carbon, and a high degree of ductility and impact resistance may be expected.

TABLE 30.—MECHANICAL PROPERTIES OF FORGED STEELS CONTAINING 0.75 TO 1.50 PER CENT CHROMIUM

Investigator	Composition, per cent				Tensile strength, lb./sq. in.	Yield strength, lb./sq in	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness	Izod impact, ft-lb.
	C	Cr	Mn	Si						
Hadfield[19]	0 12	0 84	0 18	0 08	70,600	49,300	40 0	62 1		
	0 27	1 18	0 21	0 12	88,500	58,200	33 8	61 2		
Guillet[31]	0 06	1 21		0 70	80,200	61,000	14 0	58 2	134	20 0*
	0 97	0 99	0 24	0 22	187,000	187,000	3 5	7 5	332	2 0*
Meissner[226]	0 59	0 82	0 83	0 35	144,000	85,000	7 0	47 0	286	3.0

* Reported as m-kg. The Frémont specimen was used; dimensions not given

The widest use of plain 1 per cent chromium steel is in fully heat-treated articles. The properties after quenching in oil and tempering at various temperatures are given in Table 33. The only data available on the properties after water quenching and tempering are those by Dawe[103] on a steel containing 0.31 per cent carbon, 0.91 per cent chromium, and 0.85 per cent manganese. The quenching temperature was 870°C. (1600°F.). Tensile properties are as follows:

Tempering temperature		Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent
°C.	°F.				
540	1000	140,100	124,600	16 9	58 1
595	1100	121,100	104,900	20 5	64 0
650	1200	113,700	97,100	21 7	64 8

As shown by the data in Table 33, good ductility and impact strength are found in all degrees of strength in the sections tested. It is, however, apparent that relatively low values were obtained in some cases, particularly in the less recent work. It has been a general experience that chromium steels are somewhat sensitive

TABLE 31.—MECHANICAL PROPERTIES OF ANNEALED STEELS CONTAINING 0.75 TO 1.50 PER CENT CHROMIUM

Investigator	Composition, per cent				Annealing temperature		Tensile strength, lb /sq. in.	Yield strength, lb./sq in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness	Izod impact, ft-lb.
	C	Cr	Mn	Si	°C.	°F.						
Hadfield[19]	0 12	0 84	0 18	0 08	.	..	62,700	42,500	42 5	61 2		
	0 27	1 18	0 21	0 12	..	. ..	80,600	44,800	33 0	46 8		
Arnold and Read[51]	0 84	0 99	.	.	..		97,200	42,300	22 5*	39 0		
Moore[90]	0 30	0 77	0 36	0 16	930	1705	76,500	48,200	33 0	53 5		
					1070	1960	75,000	44,100	34 0	53 5	126	7.8†
	0 34	1 05	0 32	0 05	930	1705	77,400	40,000	32 0	47.3		
Wright and Mumma[407]	0 10	0 99	0 39	0 17	900	1650	53,800	32,500‡	43 0	77 0	...	88.0
	0 20	0 97	0 38	0 19	875	1605	66,300	38,600‡	35 5	61.0	..	65 0
	0 31	1 06	0 42	0 26	875	1605	81,700	44,900‡	28 0	49 0	..	40 0
Jones[285]	0 29	0 87	0 43	.	.		74,400	40,300	34 0	57 0	142	44 0
	0 30	1 23	0 49	.	.		78,800	41,300	32 0	56 0	149	45 0
	0 30	1 47	0 47			.	77 900	41,300	34 0	59 0	150	51 0
	0 31	0 92	0 90	..			84,000	46 600	32 0	58 0	159	46 0
Rapatz[170]	0 16	1 00			670	1240	65,000	40 400	39 0	77 0		
	0 24	1 50			680	1255	83,000	56,000	29 0	72 0		

* Gage length not given.

† Guillery, m-kg per sq. cm See footnote †, Table 28

‡ For an extension under load of 0 5 per cent.

TABLE 32.—MECHANICAL PROPERTIES OF NORMALIZED STEELS CONTAINING 0.75 TO 1.5 PER CENT CHROMIUM

Investigator	Composition, per cent				Normalizing temperature		Tempering temperature		Tensile strength, lb /sq in.	Yield strength, lb /sq in	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness	Izod impact, ft-lb
	C	Cr	Mn	Si	°C	°F	°C	°F						
Moore[90]	0 34	1 05	0 32	0 05	905	1660			.....				155	12 5*
Wright and Mumma[407]	0 10	0 99	0 39	0 17	900	1650			60 000	44,400†	41 5	75		88 0
							550	1020	59,100	44,200	42 5	76		87 0
							605	1125	58,300	41,900	42 5	76	.	88 0
							665	1225	57 100	40,100	42 0	78	.	86 0
							700	1290	56 700	41,000	44 0	77	.	87 0
							750	1380	57,800	39 400	43 0	77		88 0
	0 20	0 97	0 38	0 19	875	1605			73.000	50 600	35 0	69		77 0
							550	1020	72,400	50 200	36 5	69		77 0
							605	1125	71,500	50 000	37 5	69		76 0
							650	1200	70 100	48,200	36 0	67	.	82 0
							700	1290	68 500	46,800	37 5	70	.	81 0
							750	1380	68,800	46,600	38 0	71		84 0
	0 31	1 06	0 42	0 26	875	1605			97 200	62,700	24 5	60		42 0
							550	1020	96 800	60 000	26 0	60		40 0
							605	1125	94,500	58,000	26 5	60	.	42 0
							650	1200	93,000	56,900	27 0	60	..	41 0
							690	1270	91,800	54,700	28 0	62		59 0
							750	1380	86,300	54,000	30 5	66	.	54 0
Aitchison[93] . .	0 45	1 28	0 72	0 12	870	1600			119 600	70 100	22 0	60 8		2‡
							400	750	120,500	69,900	23 2	61 0		3‡
							500	930	119,200	70,100	23 2	61 5	.	3‡
							600	1110	117 700	67,200	23 5	61 5		3‡
							650	1200	115,900	65 000	23 5	61 5		5‡
							700	1290	109,200	59,600	25 0	61 0	.	4‡
							750	1380	103,000	58,500	27 5	63 6	..	6‡
Jones[285]	0 29	0 87	0 43		830	1525			66 600	46,600	36 0	64 0	155	66
	0 30	1 23	0 49		830	1525			84,000	51 500	33 0	64 0	169	55
	0 30	1 47	0 47		830	1525			85,600	51,500	32 0	62 0	176	58
Hankins and Ford[244]	0 45	1 14	0 69	0 12	830	1525			121 000	89,600	12 5§	50 0	250	

* Guillery, m-kg per sq cm See footnote †, Table 28
† For an extension under load of 0 5 per cent
‡ Specimen 10 × 10 mm ; V-notch 2 mm deep with 0 25 mm radius.
§ Elongation in 8 in.

TABLE 33.—MECHANICAL PROPERTIES OF OIL-QUENCHED AND TEMPERED STEELS CONTAINING 0.75 TO 1.50 PER CENT CHROMIUM

Investigator	Composition, per cent				Quenching temperature		Tempering				Tensile strength, lb /sq. in.	Yield strength, lb /sq in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness	Impact value*
							Temperature		Time, hr.	Cooled in						
	C	Cr	Mn	Si	°C	°F	°C	°F								
Dickenson[73]	0.16	1.00			†	†	†	†			65,000	40,300	39	77		
	0.24	1.40			†	†	†	†			82,900	56,000	29	72		
	0.40	0.90			†	†	†	†			103,100	60,500	24	66		
	0.52	1.20			†	†	†	†			130,000	85,100	20	56		
	0.73	0.90			†	†	†	†			147,900	94,100	19	47		
Moore[80]	0.30	0.77	0.36	0.16	860	1580	695	1285	1	Air	86,700	63,800	32	69.8	167	23.8
							600	1110	1	Air	93,500	69,600	27	64.8	180	20.2
	0.34	1.05	0.32	0.05	860	1580	695	1285	1	Air	90,500	69,500	31	68 8	167	20.5
							600	1110	1	Air	100,400	78,600	27	65 8	196	16.4
	0.30	0.77	0.36	0.16	855	1570	735	1355	2⅓	Air	83,000	58,000	34	68 8	157	25 0
							555	1030	⅓	Water	103,100	74,400	25	58 2	214	9.4
	0.34	1.05	0.32	0.05	830	1525	600	1110	⅓	Water					209	17.0
					825	1515	730‡	1345‡	4¼	Air	87,800	68,100	33	69.9		
	0.34	1.05	0.32	0.05	830	1525	745	1375	1	Air					151	22.5
					820	1510	620	1150	½	Air	106,600	82,400	26	62 7		
Jones[86]	0.38	1.43	0.22	0.15	1000	1830	650	1200	2	Water	101,500	76,600	25	64	210	59
									2	Furnace	99,500	74,600	25	64	207	41
					900	1650	650	1200	1	Air	104,800	80,000	25	69	225	67
									2	Water	99,500	75,000	26	69	205	66
									2	Furnace	96,300	73,300	25	69	201	62
									6	Air	96,300	71,300	27	70	198	72
							600	1110	1	Air	112,700	89,400	22	65	233	55
									2	Air	112,000	86,000	23	65	229	55
									6	Air	105,900	81,500	24	65	225	55
							550	1020	2	Air	119,800	96,800	21	58	257	6
							500	930	6	Air	120,100	96,300	20	57	255	25
					820	1510	650	1200	2	Air	95,700	70,400	26	70	198	67
							600	1110	2	Air	105,100	81,100	23	64	223	54
							550	1020	2	Air	115,900	91,400	21	61	244	32
Aitchison[93]	0.45	1.28	0.72	0.12	870	1600	300	570			240,100	233,000	3 2	8 3		2
							400	750			222,100	191,100	9.0	32 9		5
							500	930			179,400	156,900	13 7	45 3		10

									600	1110			144,900	131,100	20 0	54 1	. .	21
									650	1200			130,000	111,600	23 0	60 8	...	42
									700	1290			116,500	96,800	26 0	63.7	...	88
									750	1380			105,500	70,100	30 5	69 8	. .	98
	0	31	1	36	0	75	0.14	860	1580	300	570		160,400	145,800	12 7	45 9	...	3
										400	750		165,800	154,600	11 7	43 2	...	3
										500	930		138,900	119,600	16 0	55 8	. .	10
										600	1110		132,600	107,600	21 0	62 5	...	17
										650	1200		121,600	94,600	23 0	66 0	...	52
										700	1290		100 800	80,000	23 0	67 9	.	90
										750	1380		90,700	66,300	31 5	70 9	. .	93
	0	75	1	29	0	34	0 16						275,700					
										500	930		198 700	185,300	10 0	27 6	.	9
										600	1110		158,600	142,500	17 0	45 9	...	25
										650	1200		142,200	123,600	20 0	51 0	.	38
										700	1290		133,600	117,200	21 0	52 2	.	48
										750	1380		120,400	87,600	26 0	58 0	. .	38
Kothny[79]	0	14	1	14	0	28		880	1615	680	1255		85,200	62,700	16 0§	76	. .	38 6
								860	1580	610	1130		98,600	80,600	13 3§	74	...	33 0
										520	970		114.300	96,300	10 3§	65	...	21 0
										450	840		118,800	91,800	10 0§	60	...	14 6
	0	19	1	08	0	92	.	860	1580	680	1255		103,100	80,600	14 5§	75	...	47 0
										550	1020		116,600	91,800	12 5§	65	...	38 0
										520	970		125,400	103,100	10.1§	64	. .	15 4
										430	805		172,700	141,200	7 3§	58	...	11 0
	0	22	0	86	0	21	.	850	1560	680	1255	...	87,400	62,700	23 0§	73	...	36 4
										600	1110		103,100	87,400	14 4§	66	. .	19 4
										550	1020		112.000	96,300	13 0§	64	. .	23.0
										500	930		123,200	103,100	12 0§	61	.	13 6
	0	35	1	50	0	70	.	820	1510	680	1255		118,800	98,600	13 0§	64	...	36 6
										650	1200		129,900	109,800	11 3§	54	...	27.3
										550	1020		165,800	141,200	7 5§	45	...	17.8
										500	930		203,900	165,800	6 3§	46	. .	9 4
	0	49	1.50		0.70		.	800	1470	680	1255	. .	129,900	103,100	11 9§	56	...	20 5
										600	1110		156,800	134,400	10.0§	45	...	16 4
										550	1020	. .	197,100	174,800	6 9§	44	...	9.4
										500	930	. .	122,800	170,300	5 4§	15	...	7 7
	0	57	1	05	0	54	. .	810	1490	680	1255	.	132,200	103,100	13 4§	61	...	23 0
										650	1200	.	138,900	109,800	13 1§	59	...	15 5
										600	1110		150,000	141,200	10 0§	49	...	8.8
										550	1020		172,300	152,300	7 8§	44	. .	7.2
	0	61	1	22	0	33	....	820	1510	680	1255	.	132,200	107,700	13 0§	50	. .	16 1
										650	1200		150,000	125,400	12 0§	45	.	12.4
										600	1110	. .	163,300	138,900	10 5§	43	. .	10.3
										550	1020	.	181,300	156,800	7 5§	36	...	5.4

TABLE 33.—MECHANICAL PROPERTIES OF OIL-QUENCHED AND TEMPERED STEELS CONTAINING 0.75 TO 1.50 PER CENT CHROMIUM.—(*Continued*)

Investigator	Composition, per cent				Quenching temperature		Tempering				Tensile strength, lb./sq. in	Yield strength, lb /sq in	Elongation in 2 in , per cent	Reduction of area, per cent	Brinell hardness	Impact value*
							Temperature		Time, hr	Cooled in						
	C	Cr	Mn	Si	°C	°F	°C	°F								
Hankins and Ford[244]	0 45	1 14	0 69	0 12	830	1525	350	660			230,000	156,800‖		1	480	12
							425	795			224,700	212,900	4 3¶	17	450	12
							500	930			192,700	179,200	6 6¶	30	392	17
							575	1065			166,900	156,800	8 6¶	36	354	50
Bullens[71]	0 64	1 04	0 28	0 17	870	1600	400	750			227,500	170,000**	5 0	13 5	477	
							500	930			212,000	155,000	8 0	19.5	444	
							600	1110			186,000	127,500	10 0	22 5	387	
Müller-Hauff and Stein[297]	0 42	1 00	0 70	0 25	850	1560	450	840	½		217 000	206,000	10 5††	57 5		398
							500	930	½		203.000	192.000	11 5††	45 0		491
							550	1020	½		189.000	177,500	13 5††	47.5		608
							600	1110	½		167,000	156,500	15 0††	50 0		702
							650	1200	½		149,000	138,500	18 0††	55 0		819
Gillett and Mack[154]	0 35	0 94	0 62	0 35	900	1650	425	795			194 500	160.000	12 0	40 6	415	23
							525	975			158 000	131 000	16 5	54 5	340	55
							625	1155			126.800	105,000	22 5	64 7	270	90
Abram[411]	0 30	1 25	0 19	0 05	925	1695	500	930	1	Water	111,800	91,400	20 0	63 0		53
							550	1020	1	Water	104,900	84,200	22 0	64 0		68
							600	1110	1	Water	93,600	65,400	25 0	67 0		74
							650	1200	1	Water	87,800	63,400	27 0	70 0		84
							700	1290	1	Water	83,800	60,000	30 0	72 0		88

* Impact specimens and units were as follows:
Moore Guillery, m-kg. per sq mm See footnote †, Table 28
Jones and Aitchison Izod, ft-lb Specimen 10 × 10 mm , V-notch, 2 mm deep, 0 25 mm radius
Kothny: m-kg Specimen 20 × 20 mm , 4 mm round notch, 5 mm deep; striking energy 75 m-kg
Hankins and Ford Izod, ft-lb Specimen 9 × 9 mm , 45-deg V-notch, 1 mm deep, 0 25 mm radius
Muller-Hauff and Stein: Reported as ft-lb. per sq in
Gillett and Mack, and Abram: Izod, ft-lb

† Dickenson's specimens were quenched from a temperature 90°C (160°F) above Ac_1 and tempered at a temperature 80°C (145°F) below Ac_1.

‡ Then tempered again for 2 hr at 630°C (1165°F) and cooled in air

§ $l = 10d$

‖ Reported as proportional limit

** Reported as elastic limit

¶ Elongation in 8 in

†† $l = 5d$.

to poor steel-making practice and to lack of balance in the other elements. Higher carbon than necessary should be avoided and manganese should range from 0.50 to 1 per cent. Lack of appreciation of the conditions required to develop the best properties retarded the use of chromium steel for many years, but with application of knowledge of these factors and methods for controlling them, 1 per cent chromium steel has properties that make it most suitable for many heat-treated parts.

69. Steels Containing 1.5 to 2.5 Per Cent Chromium.—The tensile and impact properties of the 2 per cent chromium grade are shown in Tables 34 to 38. The increased depth-hardening capacity raises the maximum strength that may be obtained in rolled and normalized sections without sacrifice of ductility. As the additional chromium increases the strength, the carbon content for a given strength is somewhat lower. In the sections under consideration the maximum safe strength developed by air cooling is about 120,000 lb. per sq. in., which may be obtained with about 0.40 per cent carbon. In thoroughly annealed material, 2 per cent chromium has very little effect on the strength.

TABLE 34.—MECHANICAL PROPERTIES OF FORGED STEELS CONTAINING 1.5 TO 2.5 PER CENT CHROMIUM

Investigator	Composition, per cent				Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness	Impact value,* m-kg
	C	Cr	Mn	Si						
Hadfield[19]	0.21	1.51	0.12	0.14	85,200	53,700	37.1	64.1		
Guillet[31]	0.89	2.14	0.11	0.28	198,000		2.5	0	364	3
McWilliam and Barnes[49]	0.20	1.98	0.12		78,800	51,500	30.5	71.0		
	0.25	1.99	0.23		86,500	53,800	30.0	68.0		
	0.32	1.98	0.23		103,700	67,200	26.0	65.0		
	0.50	1.99	0.24		120,600	71,700	20.5	66.0		
	0.65	2.07	0.22		159,800	129,900	14.5	41.0		
	0.85	2.00	0.24		170,100	116,600	10.0	18.0		

* Frémont specimen, dimensions not given.

In the oil- or water-quenched and tempered condition, 2 per cent chromium steels have the same good properties that are found with 1 per cent chromium. A higher tempering temperature is required to obtain a given strength, but in other respects

the two grades are very similar. As 1 per cent chromium is usually sufficient to give adequate depth hardening in most heat-treated parts, there has been little incentive to use 2 per cent chromium steels except in cases where somewhat lower rates of cooling are encountered or where some special property is desired.

70. Steels Containing 2.5 to 3.5 Per Cent Chromium.—It will be seen in Tables 39, 40, and 41 that in 3 per cent chromium steels in the rolled and normalized states a different condition exists than was found in the lower chromium steels. Strengths up to 200,000 lb. per sq. in. are accompanied by excellent ductility and impact resistance. This condition has been found in sections as large as 4 by 6 in. so that it is apparent that a sudden increase has taken place in capacity to retain ductility at high strengths and in large sections. A well-substantiated reason for this has not been advanced, but it is perhaps significant that it coincides with the appearance of the trigonal carbide. Chromium in this amount contributes greatly to the development of high strength; in fact, for most applications the carbon must be held below 0.35 per cent to avoid hardness in excess of 400 Brinell after normalizing. The strength of the normalized steel may be lowered by tempering.

As with lower chromium steels, the presence of 3 per cent chromium produces little effect in the annealed steel. In the fully heat-treated condition the ductility is equal or superior to that of the lower chromium steels, but there is some tendency to temper brittleness that makes it desirable to cool rapidly from the tempering temperature. In general, 3 per cent chromium steels have found their largest application in the normalized condition although some of the steel has been quenched and tempered in massive sections.

71. Mechanical Properties Developed by Transformation at Constant Temperature.—Döpfer and Wiester,[416] in conjunction with their investigation of transformation at constant temperatures, heat treated two chromium steels of the following analysis:

Steel	Composition, per cent			
	C	Mn	Si	Cr
40 Cr 0 5	0 40	0 43	0.39	0.53
40 Cr 3.0	0 40	0.47	0.52	3 10

TABLE 35.—MECHANICAL PROPERTIES OF ANNEALED STEELS CONTAINING 1.5 TO 2.5 PER CENT CHROMIUM

Investigator	Composition, per cent				Annealing temperature		Tensile strength, lb./sq in.	Yield strength, lb./sq in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness
	C	Cr	Mn	Si	°C.	°F.					
Hadfield[19]	0 21	1 51	0 12	0 14			75,000	42,500	38 1	55 9	
Austin[116]	0 33	1 96	0 13	0 05	805	1480	105,000		26 6	....	205
					850	1560	101,200	58,500	26 5	....	195
					960	1760	86,900	42,100	23 4	....	146
	0 87	2 08	0 19	0 18	805	1480	108,800	56,200	20 3	....	202
					850	1560	98,400	58,500	30 5	.. .	195
					960	1760	136,600	93,600	8.6	. ..	277
	1 00	2 09	0 29	0 17	805	1480	100,400	60,800	26 5	....	207
					850	1560	101,600	67,800	31 2	..	202
					960	1760	135,400	70,200	9 3	....	269
	1 26	2 11	0 20	0 18	805	1480	106,600	65,500	26 5	.. .	210
					850	1560	112,000	65,500	23 4	. .	215
					960	1760	122,000	70,200	18 7	...	241
Moore[90]	0 33	1 60	0 28	0 05	930	1705	79,700	35,600	29	47 3	
	0 34	2 06	0 21	0 05	930	1705	81,500	32,900	28	51.1	
McWilliam and Barnes[49]	0 20	1 98	0 12		950	1740	73,900	35,800	40 5	78	
	0 25	1 99	0 23		950	1740	78,400	35,800	39 5	74	
	0 32	1 98	0 23		950	1740	68,100	31,400	37 0	71	
	0 50	1 99	0 24		950	1740	84,200	29,100	28 0	55	
	0 65	2 07	0 22		950	1740	109,800	71,700	21 5	62	
	0 85	2 00	0 24		950	1740	89,800	42,600	32 0	63	

TABLE 36.—MECHANICAL PROPERTIES OF NORMALIZED STEELS CONTAINING 1.5 TO 2.5 PER CENT CHROMIUM

Investigator	Composition, per cent				Normalizing temperature		Tempering temperature		Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness	Izod impact, ft-lb.
	C	Cr	Mn	Si	°C.	°F.	°C.	°F.						
Moore[90]	0.33	1.60	0.28	0.05	905	1660	...	....	..	....	..	...	183	10.6*
	0.34	2.06	0.21	0.05	905	1660	..	...	.....	....	...	....	280	5.6*
McWilliam and Barnes[49]	0.20	1.98	0.12	...	950	1740	...	...	74,800	47,000	36.0	71.0		
	0.25	1.99	0.23	..	950	1740	..	....	85,300	53,800	32.0	66.0		
	0.32	1.98	0.23	..	950	1740	.	..	102,900	62,700	26.0	62.0		
	0.50	1.99	0.24	..	950	1740	...	.	136,700	94,100	20.0	55.0		
	0.65	2.07	0.22	...	950	1740	..	..	152,200	125,400	16.0	40.0		
	0.85	2.00	0.24	....	950	1740	...		159,200	116,600	12.0	34.0		
Meissner[226]	0.39	2.04	0.48	0.19	900	1650	620	1150	109,000	78,000	23.0	64.0	196	21
	0.34	2.50	0.30	0.13	900	1650	620	1150	114,000	91,000	20.0	63.0	228	32

* Guillery, m-kg. per sq. cm. See footnote†, Table 28.

TABLE 37.—MECHANICAL PROPERTIES OF OIL-QUENCHED AND TEMPERED STEELS CONTAINING 1.5 TO 2.5 PER CENT CHROMIUM

Investigator	Composition, per cent				Quenching temperature		Tempering				Tensile strength, lb /sq. in.	Yield strength, lb /sq. in	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness	Izod impact, ft-lb.
							Temperature		Time, hr	Cooled in						
	C	Cr	Mn	Si	°C	°F.	°C.	°F								
Dickenson[73] ..	0 36	2 1		..	*	*	*	*		.	105,400	73,900	25	69		
	0 47	2 2		..	*	*	*	*			123,300	89,600	21	63		
	0 64	2 2	.	...	*	*	*	*			134,500	105,400	20	56		
Moore[90]	0.33	1.60	0.28	0.05	860	1580	695	1285	1	Air	96,800	75,700	28	68 8	189	22.5‡
							600	1110	1	Air	110,900	86,700	22	62 7	211	16 1
	0.34	2.06	0 21	0.05	860	1580	695	1285	1	Air	104,800	85,500	27	68 8	200	18.7
							600	1110	1	Air	115,400	109,100	22	61 6	248	15 0
	0.33	1.60	0.28	0.05	825	1515	735†	1355†	4¼	Air	89,600	71,700	33	69 9		
					830	1525	745	1375	1	Air					163	23 1
	0 34	2 06	0 21	0 05	825	1515	735†	1355†	4¼	Air	93,200	76,200	32	70 8		
	0 33	1 60	0 28	0.05	855	1570	555	1030	⅓	Water	..	.	.		240	15 2
	0 34	2 06	0.21	0 05	855	1570	555	1030	⅓	Water	.	.	..	..	253	13 8
	0.33	1 60	0 28	0.05	820	1510	620	1150	½	Air	112,900	93,200	24	63 8		
	0 34	2 06	0 21	0 05	820	1510	620	1150	½	Air	126,300	112,000	19	57 0		
Kothny[79]	0 60	1.67	0.56		820	1510	680	1255	.	...	136,700	98,600	10 8§	45	..	15 5‖
							650	1200		..	165,800	141,200	8 8§	40	..	12 5‖
							600	1110	.		181,600	156,800	7 2§	35	...	6.0‖
							500	930			228,500	192,700	5.8§	25	. .	3 0‖
Barton[118] .. .	0 45	2 00			790	1455	705	1300	..		134,000	109,000	20 0	60 0		
							540	1000	. .		169,000	150,000	14 0	40 0		
							400	750	...	.	220,000	200,000	10 0	30 0		
	0 60	2 00			720	1330	705	1300	.		129 000	115,000	17 0	55 0		
							540	1000	. .		179,000	170,000	13.0	20 0		
							400	750	. .		229,000	190,000	9 0	30 0		
Meissner[226]	0 39	2 04	0.48	0 19	900	1650	525	980	1		172,000	155,000	14 0	49 0	330	22 0
	0 42	2 31	0 46	0 29	900	1650	525	980	1		160 000	150,000	14 0	46 0	364	12 0

* Dickenson's specimens were quenched 90°C (160°F) above Ac_1 and tempered 80°C (145°F) below Ac_1.
† Then tempered again for 2 hr at 630°C. (1165°F) and cooled in air
‡ Guillery, m-kg. per sq. cm See footnote †, Table 28.
§ $l = 10d$
‖ Reported as m-kg Specimens 20 × 20 mm. notch 4 mm in diameter, 5 mm deep Striking energy, 75 m-kg

TABLE 38.—MECHANICAL PROPERTIES OF WATER-QUENCHED AND TEMPERED STEELS CONTAINING 1.5 TO 2.5 PER CENT CHROMIUM

Investigator	Composition, per cent				Quenching temperature		Tempering temperature		Tensile strength, lb./sq. in.	Yield strength, lb./sq. in	Elongation in 2 in., per cent	Reduction of area, per cent
	C	Cr	Mn	Si	°C	°F.	°C.	°F.				
McWilliam and Barnes[49]	0 20	1 98	0 12		800	1470	400	750	153,700	150,000	12 5	40 6
							550	1020	129,900	123,200	16 0	50 7
							700	1290	92,300	71,700	28 0	70 2
	0 25	1 99	0 23	.	800	1470	400	750	197,500	174,800	12 0	42 5
							550	1020	161,200	152,200	14 5	51 5
							700	1290	105,300	91,800	25 0	68 5
	0 32	1 98	0 23	.	800	1470	400	750	224,000	203,000	9 5	37 0
							550	1020	178,300	170,200	15 0	52 2
							700	1290	122,700	105,300	22 5	67 2
	0 50	1 99	0 24		800	1470	400	750	255,600	250,900	9 0	30.3
							550	1020	200,800	190,300	13 0	42 5
							700	1290	139,800	127,700	21 0	61 5
	0 65	2 07	0 22		800	1470	550	1020	216,000	210,400	10 0	32.4
							700	1290	140,200	127,700	21 0	55.8
	0 85	2 00	0 24		800	1470	550	1020	214,400	208,200	8 5	28 0
							700	1290	141,100	129,900	20 0	51.7
Barton[118]	0 27	2 00	.	.	760	1400	705	1300	90,000	80,000	25 0	60 5
							540	1000	135,000	125,000	16.0	50 0
							400	750	170,000	150,000	12.0	55 0
	0 35	2 00	.		790	1455	705	1300	105,000	90,000	22 0	65.0
							540	1000	150,000	140,000	16 0	50 0
							400	750	190,000	180,006	10 0	35 0
Gillett and Mack[154]	0 50	1 99	0 55	0 20	800	1470	400	750	256,000	251,000	9 0	30 0

TABLE 39.—MECHANICAL PROPERTIES OF FORGED OR ANNEALED STEELS CONTAINING 2.5 TO 3.5 PER CENT CHROMIUM

Investigator	Composition, per cent				Annealing temperature		Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Izod impact, ft-lb.
	C	Cr	Mn	Si	°C	°F.					
As forged											
Hadfield[19]	0 39	2 54	0 25	0 14			121,000	66 100	26 7	52 0	
	0 41	3 17	0 28	0 18			143,300	67,200	21 6	43 8	
As annealed											
Hadfield[19]	0 39	2 54	0 25	0 14			98,500	54,800	24 5	33 8	
	0 41	3 17	0 28	0 18			106,400	48,200	24 0	35 5	
Moore[90]	0 39	2 56	0 18	0 07	930	1710	95,400	42,400	25 0	42 0	
	0 38	3 05	0 15	0 08	930	1710	95,800	41,600	24 0	44 7	
Wright and Mumma[407]	0 11	3 15	0 42	0 30	900	1650	60,300	24,800*	40 0	78 0	88
	0 19	3 04	0 45	0.28	875	1605	69,900	27,200	34 0	74 0	67
	0 30	3 14	0 52	0 27	875	1605	77,400	37,200	30 0	66 0	13
Rapatz[170]	0 22	2 90	..	. .	695	1285	92 000	69,000	27 0	74 0	

*Load for an extension of 0.5 per cent.

TABLE 40.—MECHANICAL PROPERTIES OF NORMALIZED STEELS CONTAINING 2.5 TO 3.5 PER CENT CHROMIUM

Investigator	Composition, per cent				Normalizing temperature		Tempering temperature		Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness	Izod impact, ft-lb.
	C	Cr	Mn	Si	°C.	°F.	°C.	°F.						
Moore[90]	0 38	3 05	0 15	0 08	860	1580	695	1280	93,900	75,900	29	68 8	182	22 2*
							600	1110	116,200	97,900	19	58 2	252	7.4*
	0 39	2 56	0 18	0 07	905	1660			.... .			.	356	4.4*
	0 38	3 05	0 15	0 08	905	1660			.....		.		450	2.5*
Wright and Mumma[407]	0 11	3 15	0 42	0 30	900	1650			102,500	60,500†	19 0	49 0	.	30
							550	1020	113,000	78,400†	18 0	52 0	. .	35
							607	1125	88,300	62,300†	25 0	71 0	.	39
							650	1200	80,400	55,800†	26 0	76 0		95
							689	1270	76,600	53,300†	30 0	78 0		98
							750	1380	70,100	47,100†	33 0	80 0	.	101
	0 19	3 04	0 45	0 28	875	1605		.	168,500	102,400†	15 5	41 0	.	19
							550	1020	157,800	117,400†	16 0	51 0		14
							607	1125	132,800	114,300†	19 0	60 0		25
							663	1225	104,200	87,100†	24 0	71 0		87
							700	1290	93,600	74,800†	26 0	72 0	.	100
							750	1380	84,700	64,800†	28 0	73 0	..	101
	0 30	3 14	0 52	0 27	875	1605			207,400	116,600†	10 5	27 0	.	19
							550	1020	174,200	137,900†	16 0	49 0	.	13
							607	1125	137,100	117,200†	19 0	60 0		51
							656	1215	123,000	100,800†	22 0	67 0		69
							700	1290	108,400	85,100†	25 5	71 0		88
							750	1380	96,300	73,900†	27 0	72 0	.	94

TABLE 40.—MECHANICAL PROPERTIES OF NORMALIZED STEELS CONTAINING 2.5 TO 3.5 PER CENT CHROMIUM.—(*Continued*)

Investigator	Composition, per cent				Normalizing temperature		Tempering temperature		Tensile strength, lb /sq. in.	Yield strength, lb./sq in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness	Izod impact, ft-lb.
	C	Cr	Mn	Si	°C	°F.	°C.	°F.						
Aitchison[93]	0 37	2 8			830	1525			179,200	138,900	13 5	26 1	.	12‡
							100	210	176,400	130,000	15 0	29 1	.	12‡
							200	390	181,900	149,700	13 5	30 6		11‡
							300	570	181,900	152,300	13 5	39 2	...	4‡
							400	750	173,900	153,200	14 0	39 2		7‡
							500	930	161,300	136,700	16 0	45 9	.	7‡
							600	1100	125,400	106,700	21 0	61 5	.	36‡
							700	1290	109,300	86,900	25 5	66 6	. .	98‡
Meissner[226]	0 37	2 80	0 47	0 20	900	1650	540	1000	159,000	137,000	14 0	47 0	311	8.0
							620	1150	117,000	91,000	22 0	65 0	228	27 0
	0 36	2 98	0 34	0 18	900	1650	540	1000	159,000	138,000	14 0	48 0	321	8 0
							620	1150	90 000	56,000	26 0	69 0	140	84 0
	0.26	3 07	0 49	0 33	900	1650	540	1000	170,000	130,000	13 0	43 0	340	9 0
							620	1150	110,000	88,000	22 0	67 0	228	21 0
	0 27	3 57	0 30	0 26	900	1650	540	1000	160,000	135,000	15 0	53 0	321	10 0
							620	1150	102,000	*78,000	23 0	71 0	198	73.0

* Guillery, m-kg. per sq. cm. See footnote †, Table 28

† For an extension under load of 0.5 per cent.

‡ Specimen 10 × 10 mm., V-notch 2 mm. deep, 0.25 mm radius.

TABLE 41.—MECHANICAL PROPERTIES OF OIL-QUENCHED OR WATER-QUENCHED AND TEMPERED STEELS CONTAINING 2.5 TO 3.5 PER CENT CHROMIUM

Investigator	Composition, per cent				Quenching temperature		Tempering				Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness	Izod impact, ft-lb.
	C	Cr	Mn	Si	°C.	°F.	Temperature °C.	Temperature °F.	Time, hr	Cooled in						
Oil quenched																
Dickenson[73]	0.23	2.9			*	*	*	*			91,800	69,500	27	74		
	0.33	3.3			*	*	*	*			103,100	76,200	25	70		
	0.41	3.1	..		*	*	*	*	.		107,600	78,400	27	69		
	0.76	2.9	...		*	*	*	*	..	..	130,000	100,900	22	66		
Moore[90]	0.39	2.56	0.18	0.07	860	1580	695	1285	1	Air	107,700	92,700	27	66.8	200	18.7†
							600	1110	1	Air	142,700	121,600	19	54.7	270	11.5†
	0.38	3.04	0.15	0.08	860	1580	695	1285	1	Air	101,700	90,200	27	66.8	212	15.0†
							600	1110	1	Air	144,100	115,100	18	57.0		
	0.39	2.56	0.18	0.07	825	1515	735‡	1355‡	4¼	Air	94,100	79,700	30	69.9		
					830	1525	745	1375	1	Air			.	...	172	20.6†
	0.38	3.04	0.15	0.08	825	1515	735‡	1355‡	4¼	Air	93,200	84,200	32	70.8		
					830	1525	745	1375	1	Air	. .	..	....	....	173	19.4†
	0.39	2.56	0.18	0.07	855	1570	555	1030	⅓	Water	. .		..	...	300	9.4†
	0.38	3.04	0.15	0.08	855	1570	555	1030	⅓	Water			....	....	287	10.1†
	0.39	2.56	0.18	0.07	820	1510	620	1150	½	Air	137,100	121,000	21.0	59.4		
	0.38	3.04	0.15	0.08	820	1510	620	1150	½	Air	139,800	121,000	18.0	59.4		
Jones[98]	0.43	3.05	0.21	0.09	1000	1830	650	1200	2	Water	120,600	98,800	25	67	253	59
									2	Furnace	115,000	93,500	25	68	244	27

							900	1650	690	1275	2	Air	101,300	82,600	27	70	209	75
									650	1200	1	Air	121,200	99,700	23	69	255	63
											2	Water	114,900	90,700	25	70	246	65
											2	Furnace	110,900	87,200	25	70	236	33
											6	Air	106,500	86,300	27	70	224	73
									600	1110	1	Air	147,400	125,400	19	59	307	22
											2	Air	138,900	116,300	20	61	296	24
											6	Air	130,000	108,400	22	64	271	37
									550	1020	2	Air	165,100	145,200	16	56	342	13
									500	930	6	Air	186,600	169,800	14	47	391	5
							820	1510	650	1200	2	Air	107,600	85,600	26	70	225	68
									600	1110	2	Air	132,400	112,000	21	64	281	28
									550	1020	2	Air	157,200	142,500	18	59	325	16
Aitchison[93]	0	37	2	8			830	1525	400	750			207,000	201,600	13	0	43 2	...	6
									500	930			182,100	177,900	10	5	27 6	...	9
									600	1110		....	138,000	125,400	20	0	60 4	...	28
									650	1200			121,900	105,300	24	0	62 6	...	92
									700	1290		....	110,700	92,300	25	0	67 8	...	98
									750	1380			98,600	83,400	29	0	70 8	...	111
Meissner[226]	0	21	2	89	0	38	0	16	900	1650	525	980	1	Air	164,000	156,000	14	0	53 0	340	13
	0	27	3	57	0	30	0	26	900	1650	525	980	1	Air	167,000	142,000	14	0	54 0	364	18
Water quenched																					
Meissner[226]	0	21	2	89	0	38	0	16	900	1650	600	1110	1	Air	125,000	110,000	18	0	63 0	269	16
	0	27	3	57	0	30	0	26	900	1650	600	1110	1	Air	125,000	105,000	20	0	65 0	261	45
	0	26	3	07	0	49	0	33	900	1650	600	1110	1	Air	133,000	117,000	19	0	61 0	269	11

* Dickenson's specimens were quenched from a temperature 90°C. (160°F) above Ac_1 and tempered at a temperature 80°C. (145°F.) below Ac_1.

† Guillery, m-kg. per sq. cm. See footnote †, Table 28

‡ Then tempered again for 2 hr at 630°C (1165°F) and cooled in air.

One set of specimens of each steel was quenched in oil at 25°C. (75°F.) and the other set was quenched into hot baths as follows:

Steel	Bath	Temperature		Time, min.
		°C.	°F.	
40 Cr 0.5	Lead-tin	300	570	1
40 Cr 0.5	Lead-tin	300	570	10
40 Cr 3.0	Oil	285	545	1
40 Cr 3 0	Oil	285	545	90

The specimens were subsequently tempered at temperatures from 400 to 700°C. (750 to 1290°F.). The properties are shown in Figs. 81 and 82. It appears that the quench into the high-temperature bath produced about the same properties as the low-temperature oil quench. This is of interest as the transformation-rate data indicate that chromium may be a desirable component of steels intended for such heat treatment.

B. EFFECT OF MASS ON TENSILE AND IMPACT PROPERTIES

The effect of mass in the heat treatment of steel, that is, the influence of the lowered rate of cooling that results from increase of section on the transformation of austenite, has been recognized for many years as one of the primary factors leading to the widespread use of alloy steel. It is well known that carbon steels cannot be satisfactorily hardened in sections over 3 in. in diameter, and that in smaller sections of carbon steel, although a suitable hardness can be obtained, the impact resistance and ductility may be of a low order of magnitude. This fact has led to many surveys on hardness as affected by section and, while these are valuable for obvious reasons, practical utilization of steel in larger sections requires a knowledge of other factors. The poor properties resulting from too great a section appear to be caused primarily by cooling rates that allow a small ferrite network to be precipitated at the pearlite point. In exaggerated cases where the ferrite network is readily visible, the impact strength is lowered to extremely low values.

In carbon steels, mass effect becomes apparent in sections over 0.5 in. in diameter,* so that alloy steels must be used in most

* This has been discussed in detail in "The Alloys of Iron and Carbon," Vol. II,[478] Chap. VII.

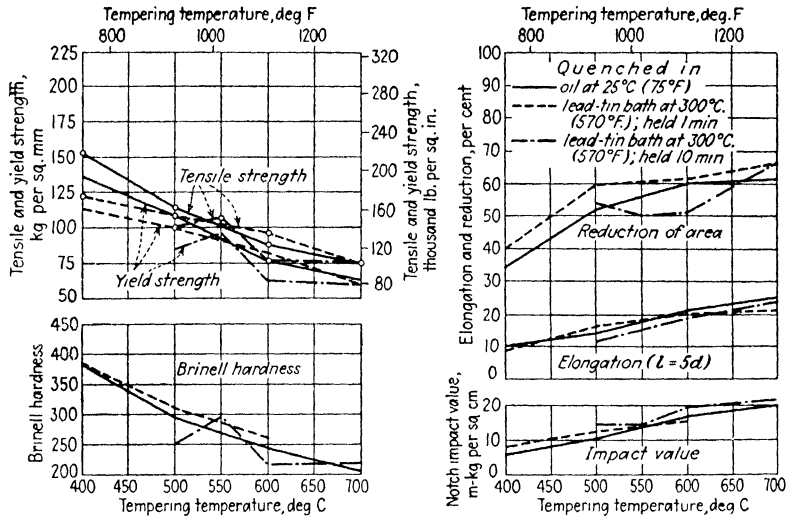


FIG. 81.—Effect of holding at constant subcritical temperatures on the mechanical properties of a 0.40 per cent carbon, 0.5 per cent chromium steel, quenched from 800°C. (1470°F.) as shown and subsequently tempered 30 min. at indicated temperatures and air cooled. (*Döpfer and Wiester.*[416])

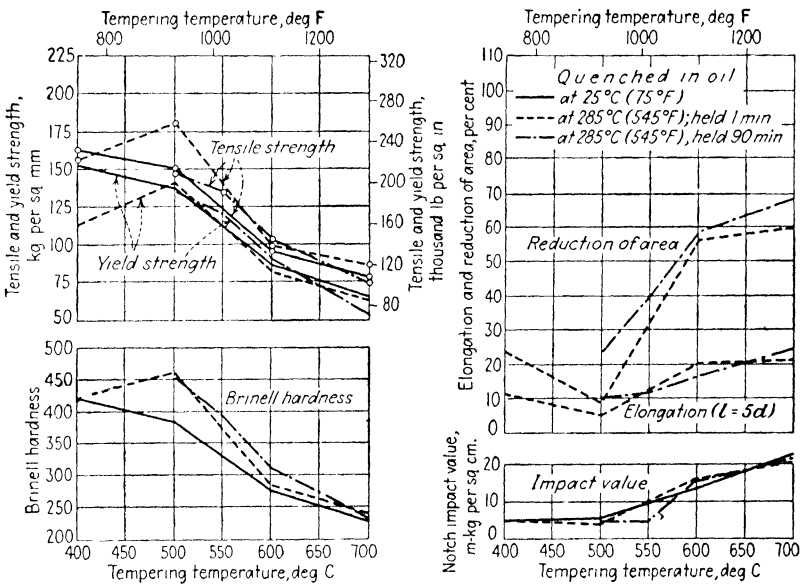


FIG. 82.—Effect of holding at constant subcritical temperatures on the mechanical properties of a 0.40 per cent carbon, 3 per cent chromium steel, quenched from 850°C. (1560°F.) as shown and subsequently tempered 30 min. at indicated temperatures and air cooled. (*Döpfer and Wiester.*[416])

engineering applications where it is desired to develop full resistance to static and dynamic loading. Chromium has been used for this purpose in varying amounts, depending on the section and application. In small parts as little as 0.50 per cent has been effective. Sections up to 2 to 3 in. in diameter require 1 to 2 per cent chromium, and in very large sections 2.5 to 3.5 per cent chromium is necessary. A discontinuous increase in capacity for overcoming mass effect has been observed at about 2.5 per cent chromium and, while the cause has not been demonstrated, it appears reasonable to assume that the improved deep-hardening effect may be related to the appearance of the trigonal carbide.

Mass effect also governs the amount of carbon to be used for a given application. It is essential that the steel be fully hardenable but that cracking be avoided. In the low-alloy steels, such as the 1 per cent chromium type, the carbon should be limited to about 0.40 per cent if the material is to be water hardened. The amount may be raised somewhat in moderately large sections. With higher chromium content the carbon content may be reduced materially, although the higher chromium steels are ordinarily used in heavier sections where the effect of the carbon content is not so critical.

72. Early Data on the Effect of Mass.—Among the early workers who have studied mass effect, Grenet[67] showed the effect of section on the Brinell hardness of a normalized steel containing 0.59 per cent carbon, 0.54 per cent manganese, 0.19 per cent silicon, and 1.82 per cent chromium. Specimens were normalized from various temperatures as shown below:

Section		Brinell hardness after normalizing at		
mm.	in.	790°C. (1455°F.)	820°C (1510°F.)	870°C (1600°F.)
10 × 10	0 39 × 0.39	312	340	555
20 × 20	0 79 × 0 79	241	255	444
30 × 30	1 18 × 1 18	234	261	321

Kothny[79] made tests to determine uniformity of hardening in 80-mm. (3.15-in.) diameter sections of 1 to 1.5 per cent chromium steels with varying carbon content after oil quenching and

TABLE 42.—EFFECT OF MASS ON MECHANICAL PROPERTIES OF LOW-CHROMIUM STEELS*

Steel	Composition, per cent				Quenched in oil from		Tempered at		Distance of specimen from surface		Tensile strength, lb/sq in.	Yield strength, lb/sq in	Elongation, $l = 10d$, per cent	Reduction of area, per cent	Impact value,† m-kg.
	C	Cr	Mn	Si	°C	°F.	°C	°F.	mm.	in					
AI	0 14	1 14	0 28	0 17	860	1580	550	1020	8	0 315	93,600	73,800	14 5	70	34 6
									15	0 591	92,200	72,000	15 1	71	28 3
									27	1 062	79,500	59,600	19 4	72	21.5
									35	1 378	79,500	56,800	19 1	71	19 5
AII	0 19	1 08	0 92	0 14	860	1580	550	1020	8	0 315	112,100	95,100	13 3	71	22 0
									15	0 591	107,900	91,800	13 8	67	19 3
									27	1 062	103,700	85,200	13 8	67	23 5
									35	1 378	99,400	82,300	14 3	67	20 0
C	0 35	1 50	0 70	0 25	820	1510	680	1255	8	0 315	116,300	92,300	12 5	64	8 8
									15	0 591	116,300	89,400	12 5	64	8 8
									27	1 062	112,200	89,400	11 4	55	9 1
									35	1 378	113,600	92,300	11 9	55	6 9
D	0 49	1 50	0 70	0 27	800	1470	650	1200	8	0 315	133,500	106,500	12 5	58	6 6
									15	0 591	127 800	102,200	12 5	59	6 6
									27	1 062	125 000	99,400	12 5	56	6 7
									35	1 378	125 000	99,400	13 0	45	5 3
EI	0 56	1.04	0 54	0 35	820	1510	650	1200	8	0 315	139,100	110,800	11 6	47	6 7
									15	0 591	139 100	110,800	4 2	46	6 4
									27	1 062	142 000	112,200	10 5	49	6 0
									35	1 378	142 000	112,200	10 6	45	5 6
EII	0 60	1.67	0 56	0 32	820	1510	680	1255	8	0 315	142 000	120,700	11 0	44	4 7
									15	0 591	139 100	110,800	11 4	44	4.4
									27	1 062	142 000	106,500	11 2	46	4 6
									35	1 378	142,000	107,900	10 9	47	4 9

* Kothny.[79]
† Specimen 10 × 10 × 70 mm. Notch 45 deg., 2 mm deep.

tempering. The results are shown in Table 42. It will be noted that the low-carbon steels failed to harden throughout, whereas the steels above 0.35 per cent carbon were of uniform hardness throughout the section. The effect of section may be estimated by comparison with test results on 22-mm. (0.87-in.) bars shown in Table 33. The tensile and impact strengths in the smaller section were somewhat higher so that it would appear that

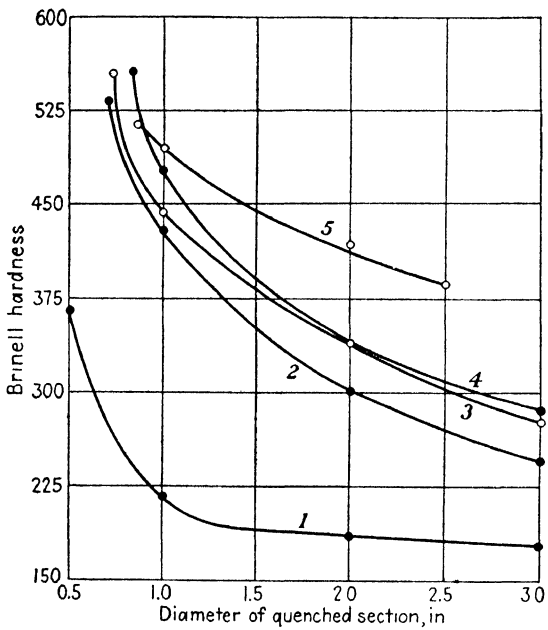


FIG. 83.—Effect of nickel and chromium on the influence of mass in heat treatment. Compositions and quenching temperatures are given in Table 43. (*Janitzky.*[110])

80 mm. (3.15 in.) diameter is too great a section for this type of steel and heat treatment.

Janitzky[110] carried out similar tests by water quenching specimens of different size. His results are shown in Fig. 83. Compositions and quenching temperatures are given in Table 43. It will be seen that the hardness fell off with section in all the steels tested. The rate of drop was approximately the same in the chromium, nickel, and low-chromium-nickel steels but was less than in carbon and greater than in high-chromium-nickel steels.

TABLE 43.—COMPOSITION AND QUENCHING TEMPERATURES OF STEELS USED BY JANITZKY[110]

Steel No.	Composition, per cent				Water quenched at	
	C	Mn	Ni	Cr	°C.	°F.
1	0 29	0 87	. .	. . .	870	1600
2	0 32	0 56	3 25	. . .	790	1450
3	0 33	0 56		0 74	870	1600
4	0 34	0 50	1 20	0 56	835	1535
5	0 29	0 37	2 22	0 97	820	1510

The effect of section on tensile properties of a steel containing 0.31 per cent carbon, 0.85 per cent manganese, and 0.91 per cent chromium was determined by Dawe[103] after water quenching and tempering at various temperatures. Results are shown in Table 44. It will be noted that a substantial reduction of yield and tensile strengths resulted from an increase in section over

TABLE 44.—EFFECT OF MASS ON MECHANICAL PROPERTIES OF A WATER-QUENCHED 0 31 PER CENT CARBON, 0 91 PER CENT CHROMIUM STEEL*

Diameter of section treated, in.	Quenching temperature		Tempering temperature		Tensile strength, lb./sq in	Yield strength, lb./sq. in.	Elongation in 2 in , per cent	Reduction of area, per cent
	°C.	°F.	°C	°F.				
⅞	870	1600	540	1000	140,100	124,600	16 9	58 1
1					138,100	124,900	17 0	57.9
1½					122,200	101,400	18 1	60 8
2†					113,100	94,400	20 7	61 3
⅞	870	1600	595	1100	121,100	104,900	20 5	64 0
1					116,500	99,700	20 6	63 8
1½					109,700	86,800	21.9	65 0
2†					105,700	83,800	21.8	65 0
⅞	870	1600	650	1200	113,700	97,100	21.7	64 8
1					112,800	96,400	21 9	66 5
1½					103,500	78,300	23.7	67.2
2†					99,400	77,900	24 2	68.5

* Dawe.[103]

† Square bar.

1 in. in diameter. Although the loss of strength was pronounced, the ductility was correspondingly improved so that even in the 2-in. square section, the effect of mass was not serious.

73. Recent Data on the Effect of Mass.—Kallen and Schrader,[286] as shown in Fig. 84, determined the tensile and Charpy impact strengths of a steel containing 0.31 per cent carbon, 0.66 per cent manganese, and 0.86 per cent chromium in sections

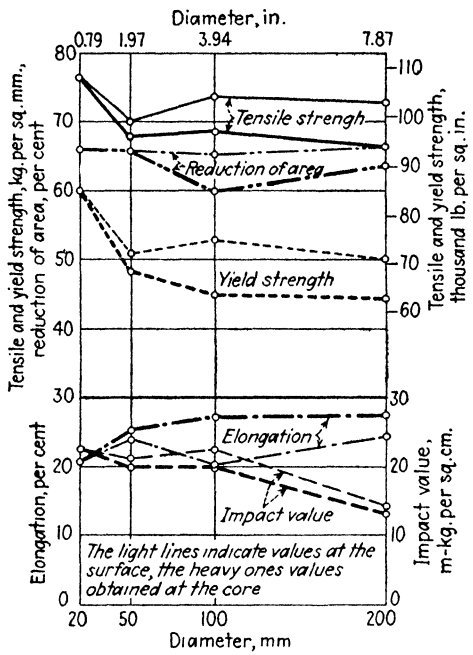


FIG. 84.—Effect of mass on the mechanical properties of steel containing 0.31 per cent carbon and 0.86 per cent chromium. (*Kallen and Schrader.*[286])

from 20 to 200 mm. (0.79 to 7.87 in.) in diameter. It will be seen that little deterioration of properties was found with increase in section up to 100 mm. (3.94 in.) in diameter. At a 200-mm. diameter some loss of impact strength was found. Although sections up to 100 mm. (3.94 in.) in diameter were found to have good properties, this may be considered to be near the ultimate safe section for the S.A.E. 5100 grade of steel. Because of practical difficulties in controlling heat treatment consistently, sections of this size would normally be made from a steel of higher alloy content.

Genders and Davidson, as reported by Greaves,[449] carried out tests on a large forging of the following composition: 0.35 per cent carbon, 0.46 per cent manganese, 0.18 per cent silicon, and 2.64 per cent chromium. The ingot was forged to outside diameters of 7.5, 10, and 15 in. and bored with a 3-in. diameter hole. Longitudinal and transverse tests were taken after oil hardening at 850°C. (1560°F.) and tempering successively at 600, 640, and 700°C. (1110, 1185, and 1290°F.) with air cooling and finally oil quenching and tempering at 650°C. (1200°F.) followed by oil quenching as shown in Table 45. The impact strength was low in the larger sections, but this was apparently due to tendency of the steel toward temper brittleness rather than to lack of

TABLE 45.—EFFECT OF MASS AND DIRECTION OF SPECIMEN ON MECHANICAL PROPERTIES OF A 0.35 PER CENT CARBON, 2.64 PER CENT CHROMIUM STEEL, OIL QUENCHED FROM 850°C. (1560°F.) AND OIL TEMPERED AT 650°C. (1200°F)*

External diameter, in.	Location of test specimen	Tensile strength, lb./sq. in.	Yield strength, lb./sq in	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness	Izod impact, ft-lb.
			Longitudinal				
15	Outside	99,900	75,000	20	65	212	17
	Middle of wall	107,100	62,100	20	48	217	7
	Bore	96,400	72,900	22	43	207	13
10½	Outside	101,100	75,900	27	67	214	44
	Middle of wall	99,600	75,500	26	65	212	33
	Bore	97,900	73,000	27	64	208	50
7½	Outside	101,400	77,000	28	70	218	83
	Bore	99,600	75,500	28	68	214	92
			Transverse				
15	Outside	100,800	75,100	24	56	214	13
	Middle of wall	105,800	64,500	19	39	218	5
	Bore	98,000	73,000	12	19	210	10
10½	Outside	101,400	76,800	21	40	215	14
	Middle of wall	99,900	75,100	18	35	214	14
	Bore	99,000	74,400	17	30	212	11
7½	Outside	99,400	75,500	21	44	211	28
	Bore	99,000	75,300	20	37	213	30

* Genders and Davidson according to Greaves.[449]

depth-hardening capacity or change in grain size. Tests on solid cylinders, 1, 2, and 7 in. in diameter, after water quenching from 820°C. (1510°F.) and tempering at 625°C. (1335°F.) followed by cooling in air, oil, or water, are shown in Table 46. In the 7-in. section the strength was lower although the ductility and impact strength were correspondingly higher.

TABLE 46.—EFFECT OF MASS ON MECHANICAL PROPERTIES OF A 0.35 PER CENT CARBON, 2.64 PER CENT CHROMIUM STEEL WATER QUENCHED FROM 820°C. (1510°F.) AND TEMPERED 2 HR. AT 625°C. (1155°F.)*

Size of cylinder, in.	Tempering medium	Tensile strength, lb./sq. in.	Yield strength, lb /sq. in	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness		Izod impact, ft-lb.
						Distance from axis of cylinder, in	Number	
1	Air	123,000	104,200	25 0	64 0	Nil	255	
	Oil	131,300	113,800	22 0	63 0	Nil	274	
	Water	133,000	112,900	22.0	60 0	Nil	280	
2	Air	130,800	112,900	22 0	64 0	Nil	269	28
	Oil	130,400	113,800	22 0	64 0	Nil	280	44
	Water	140,200	126,000	18 0	59 0	Nil	216	39
7	Water	123,600	99,400	24 0	66 0	3 1	255	
						2 3	237	42
		109,200	83,700	26 0	68 0	1 5	232	
						0 75	223	53
		107,700	81,500	26 0	68 0	Nil	226	
						0 75	223	66
		106,200	81,300	26 0	68 0	1 4	222	
						2 3	225	60
		116,200	92,400	25 0	68 0	3 0	245	

* Genders and Davidson according to Greaves.[449]

C. MISCELLANEOUS MECHANICAL PROPERTIES

There are a few data available on the miscellaneous mechanical properties of low-chromium engineering steels which are summarized in the following sections. Included in these are values for modulus of elasticity, torsion, fatigue resistance, and information on the susceptibility of the low-chromium steels to temper brittleness.

74. Modulus of Elasticity.—Measurements of modulus of elasticity require a degree of precision in measurement of strain that makes it necessary to discriminate very carefully between the reported values.

TABLE 47.—MODULI OF ELASTICITY AND RIGIDITY OF CHROMIUM SPRING STEELS

Investigator	Steel	Composition, per cent				Quenching			Tempering temperature		Modulus of elasticity, million lb /sq. in.	Modulus of rigidity, million lb /sq. in.
						Temperature		Medium				
		C	Cr	Mn	Si	°C.	°F.		°C.	°F		
Hankins, Hanson, and Ford[181]	S1	0 60	0 09	0 77	0 21	850	1560	Air			30 2	
						950	1740	Oil	400	750	29.5	11 9
									400	750	29.7	11 6
									450	840	29 8	11 8
									450	840	28 7	11 7
									500	930	29 8	11 8
									500	930	30 0	11 9
									550	1020	30 1	11 8
									550	1020	29 7	11 8
Hankins and Ford[244] ...	S3	0 60	0 56	0 62	0 26	815	1500	Air			30 8	
						800	1470	Oil	400	750	30 7	11 9
									400	750	30 6	12 2
									500	930	30 2	12 0
									500	930	30 5	12 2
									600	1110	30 5	12 2
									600	1110	30 5	12.0
	S8	0 46		0 51	0 09	810	1490	Water	510	950	30 5	
									510	950	30 2	
									550	1020	30 2	
									550	1020	30 2	
	S4	0 45	1 14	0 69	0 12	830	1525	Air			30 3	
						830	1525	Oil	350	660	29 9	11 3
									350	660	29 8	11 4
									425	795	29 8	11 4
									425	795		11 5
									500	930	30 0	11 4
									500	930		11 4
									575	1065	30 1	11 5
									575	1065	30 2	11 6

Reliable determinations have been carried out by Hankins, Hanson, and Ford[181,244] and by Abram.[410] The former obtained the results given in Table 47 for heat-treated spring steel. Abram's[410] report of a carefully conducted series of tests with the specific purpose of determining modulus of elasticity includes data on a 2 per cent chromium steel, oil quenched from 850°C. (1560°F.) and tempered as shown in the tabulation below.

Composition, per cent				Tempering temperature		Modulus of elasticity, lb./sq. in.
C	Cr	Mn	Si	°C.	°F.	
0.33		0 72	0 16	.		29,970,000
				600	1110	29,880,000
0 40	1 97	0 53	0 25	625	1200	30,210,000

Matsushita[88] tested 0.6 per cent carbon steels containing up to 3 per cent chromium, but his results were abnormally high for the low-chromium steels.

It is apparent from the foregoing that chromium raises the elastic moduli, but in the range of 0 to 3.5 per cent chromium the increase is so small as to be insignificant for practical purposes.

75. Torsion Tests.—Torsion tests have been made on chromium spring steels by Hankins and Ford.[244] Values for steels *S*3 and *S*4, the composition of which is given in Table 47, are reproduced in Table 48.

Few measurements of the shearing properties of plain chromium steels have been reported. Portevin[47] tested Guillet's[39] chromium steels, and Lyse and Godfrey[394] tested a number of steels containing other alloys in addition to chromium. The ratio of shearing to tensile properties and Poisson's ratio were unaffected by the addition of chromium.

76. Fatigue Strength.—Studies of the fatigue limit have been restricted to a relatively small number of steels in comparison with the tremendous amount of work that has been done on this subject. However, enough tests have been made to demonstrate that chromium steels have the same fatigue characteristics as the other low-alloy types, with the exception of silicon steel which has a higher ratio of fatigue to ultimate strength. Available data are summarized in Table 49.

A number of carbon and alloy steels including chromium and chromium-nickel steels were tested by Houdremont and Mailänder[247] who found a constant relation between tensile strength and fatigue limit (Fig. 85) and tensile strength plus yield strength and fatigue limit (Fig. 86) irrespective of analysis or heat treatment. These conclusions were amplified by Mailänder[453] in later work in which notched and unnotched specimens of various shapes and degrees of finish were used. All the low-alloy steels gave the same result, namely, a constant ratio between fatigue and tensile strength.*

TABLE 48.—RESULTS OF TORSION TESTS ON CHROMIUM SPRING STEELS*

Steel No.	Quenching			Tempering temperature		Brinell hardness	Proportional limit in torsion, lb./sq. in.	Modulus of rupture, lb./sq. in.	Twist in 4 in., deg.
	Temperature		Medium	°C.	°F.				
	°C.	°F.							
S3	800	1470	Oil	400	750	508	116,400	199,400	585
				500	930	434	106,300	160,000	890
				600	1110	359	78,400	135,200	1018
S4	820	1510	Oil	350	660	470	118,700	201,000	259
				425	795	443	114,300	185,900	203
				500	930	385	96,300	157,500	585
				575	1065	337	78,400	144,000	894

* Hankins and Ford.[344]

77. Temper Brittleness.—Temper brittleness (the name given by Dickenson in discussion of a paper by Philpot[70]) became of considerable interest with the development of heat-treated automotive and airplane steels. It was observed that many steels, which otherwise were of excellent quality, had extremely poor impact strength after quenching and tempering. Intensive investigation by many workers[63,70] demonstrated that it might be corrected by rapid cooling from the tempering furnace, and tests were made on a wide variety of steels to determine whether the alloy content aggravated the condition. As temper brittleness has later been found to be common to all steels and is developed in varying degree under a wide range of conditions, it was

* The relation between endurance limit and other properties is discussed in detail in "The Alloys of Iron and Carbon," Vol. II,[478] Chap. XI.

TABLE 49.—FATIGUE STRENGTH OF LOW-CHROMIUM STEELS

Investigator	Composition, per cent				Quenching			Tempering temperature		Tensile strength, lb /sq in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Izod impact, ft-lb.	Brinell hardness	Fatigue limit, semirange, lb./sq. in.
					Temperature		Medium									
	C	Cr	Mn	Si	°C.	°F.		°C.	°F							
Gillett and Mack[154] ...	0 35	0 94	.	. .	900	1650	Oil	425	795	194,500	160,000	12 0	40 6	23	415	78,000*
								525	975	158,000	131,000	16 5	54 5	55	340	80,000*
								625	1155	126,700	105,000	22 5	64 7	90	270	57,000*
Hankins and Ford[244] ..	0 60	0 56	0 62	0 25	800	1470	Oil	400	750	171,400		. .		2 2	469	107,000 to 116,500
								500	930	153,300	.		.	9.0	413	96,300
								600	1110	102,000		.	..	22 5	339	85,100
Hankins and Ford[244] ..	0 45	1 14	0 69	0 12	830	1525	Oil	425	795	212,800		.		12 5	450	100,800
								500	930	178 100			...	16 9	393	87,300
								575	1065	156,800	.	.		50 1	355	85,100

* Approximate.

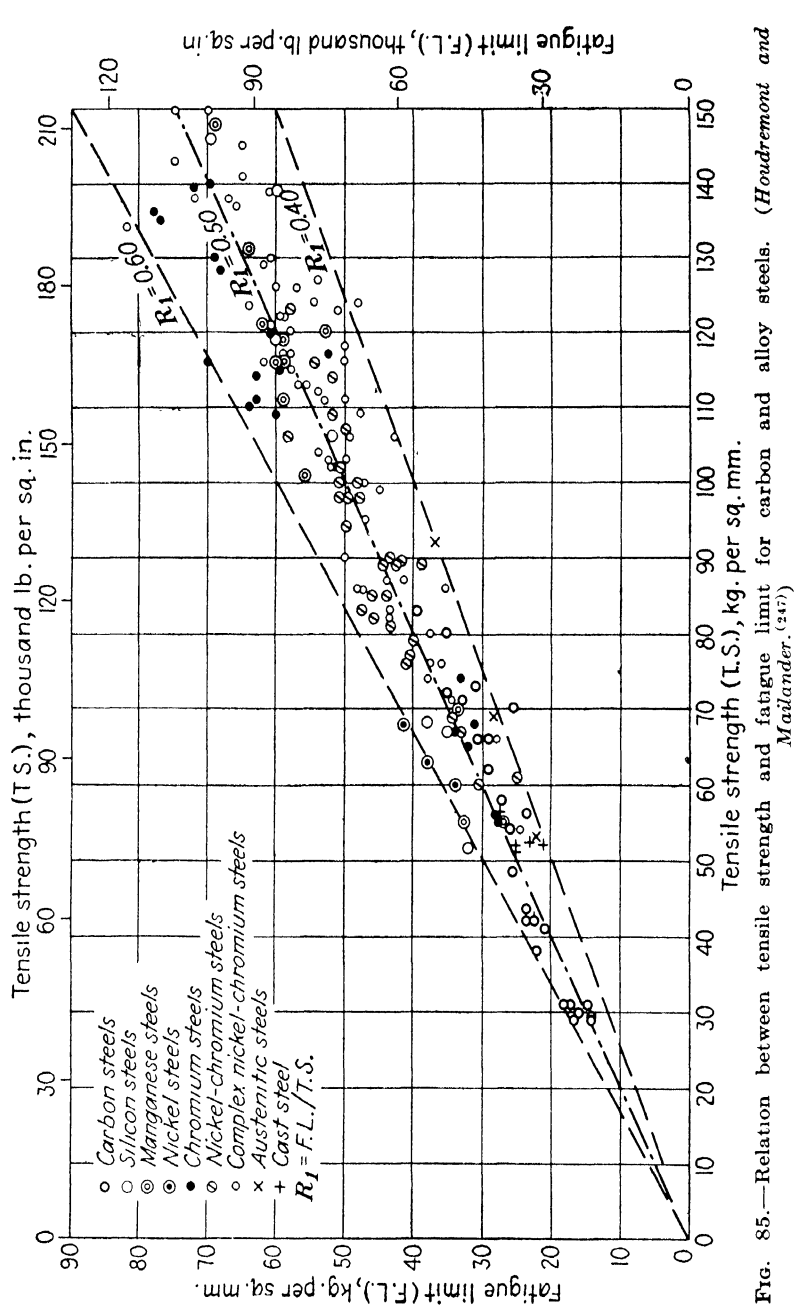


FIG. 85.—Relation between tensile strength and fatigue limit for carbon and alloy steels. (*Houdremont and Mailander.*[245])

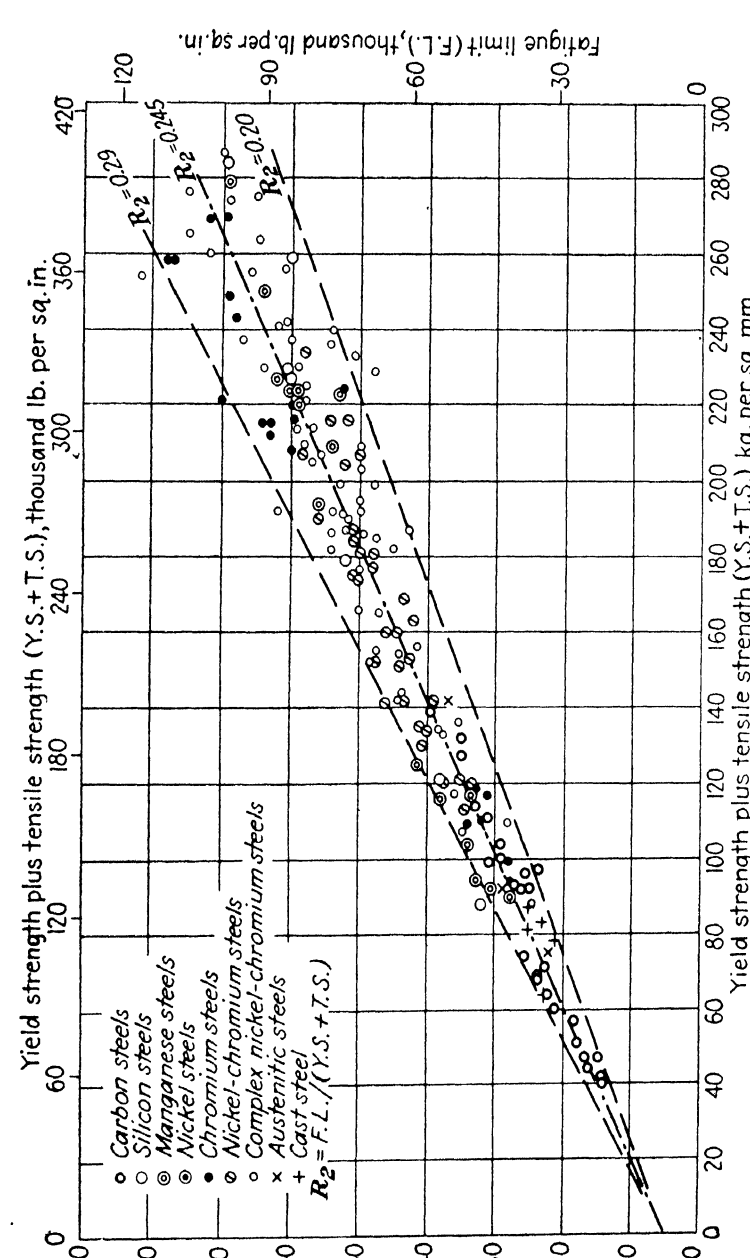


FIG. 86.—Relation between tensile strength plus yield strength and fatigue limit for carbon and alloy steels. (*Houdremont and Mailander* [247])

natural that individual investigators using different methods of heat treatment and test came to widely varying conclusions on the influence of alloys and methods of production. Chromium has at various times been considered to aggravate temper brittleness, but the evidence indicates that it is no more harmful than other alloys, excepting molybdenum. Chromium appears to increase temper brittleness of plain carbon steel, but sufficient work has not been carried out to determine its effect in comparison with other alloying elements.

TABLE 50.—EFFECT OF METHOD OF COOLING AFTER TEMPERING ON THE IZOD IMPACT VALUE OF CHROMIUM STEELS*

Composition, per cent				Tempered at 650°C. (1200°F.)		Tempered at 750°C. (1380°F.)	
				Izod impact, ft-lb, after cooling		Izod impact, ft-lb., after cooling	
C	Cr	Mn	Si	In water	Slowly	In water	Slowly
0 20	1 85	0 14	0 05	105 2	105 7	113 2	113 6
0 22	2 80	0 10	0 08	99 7	98 7	111 7	108 3
0 21	3 88	0 18	0 10	97 4	50 0	111 9	106 0
0 29	5 54	0 08	0 12	88 7	22 3	108 8	93.2

* Dickie.[239]

The mechanism by which temper brittleness is developed has been studied exhaustively and many explanations have been advanced without adequate experimental substantiation. Practically all have agreed that the brittleness is caused by change in the character of the carbide, nitride, phosphide, or oxide soluble in the range of 400 to 600°C. (750 to 1110°F.). Dickenson,[73] Rogers,[91] Grenet,[124] Andrew and Dickie,[174] and Honda and Yamada[200] considered carbide precipitation in the grain boundaries to be responsible. Precipitation of phosphides, nitrides, and oxides has been discussed by Andrew, in discussion of a paper by Rogers,[91] Greaves and Jones,[85,155] Griffiths,[157] and Houdremont and Schrader.[391] The formation of complex carbides has also been studied by Maurer and Hohage[100] and by Bishof.[415] Several others have contributed to the discussion, but in no case have the opinions been sufficiently well founded to give a sound

explanation, much less a cure for susceptibility to this form of embrittlement.

Dickie[239] carried out tests on a series of steels with a graduated chromium content, with the results shown in Table 50. The steels were oil quenched, reheated to the tempering temperature, and either water quenched or cooled slowly. The samples were subsequently tempered at the lowest temperature that could be relied on to induce temper brittleness with the minimum of additional softening. Electric-resistance and magnetic tests on these samples were considered to indicate that chromium lowered the carbide solubility at the initial tempering temperatures.

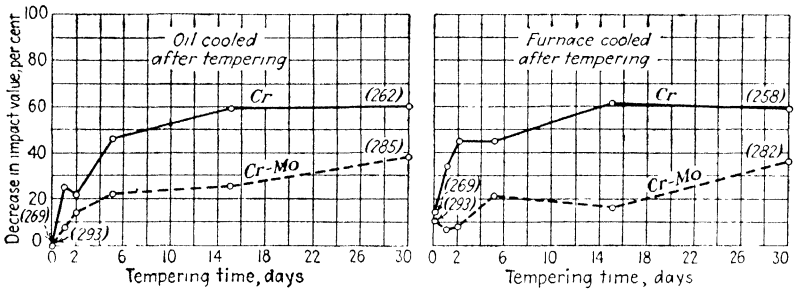


FIG. 87.—Temper brittleness of 0.40 per cent carbon, 0.90 per cent chromium steel, tempered at 600°C. (1110°F.), as compared with a similar steel containing molybdenum (0.32 per cent carbon, 1.12 per cent chromium, 0.35 per cent molybdenum), similarly treated. The figures in parentheses are the Brinell hardness numbers. (*Houdremont and Schrader.*[391])

Houdremont and Schrader[391] tempered quenched steels for long periods and, as shown in Fig. 87, the plain chromium steel (0.40 per cent carbon, 0.62 per cent manganese, 0.19 per cent silicon, and 0.90 per cent chromium) lost impact strength rather rapidly compared with a similar steel containing molybdenum. Their work showed that the rate of cooling after tempering was a secondary factor and that after long tempering periods even rapidly cooled specimens became brittle. In steels of substantially similar analysis the susceptibility to temper brittleness varied greatly but could not be related to impurities or method of manufacture. Similar results were found by Bishof[415] in a steel containing 1.5 per cent chromium. That the method of manufacture has an important influence on the susceptibility to temper brittleness and that this susceptibility may be controlled by proper manufacturing procedure has been contended, but nothing definite has been published on this phase of the subject.

D. EFFECT OF LOW AND HIGH TEMPERATURES

As the temperature is lowered steel increases in tensile strength, loses impact strength, and eventually loses static ductility. Chromium in small amounts has little effect on strength at low temperatures but tends to lower the temperature at which loss of toughness occurs. Although the mechanism producing loss of impact strength is not known, it has been found that rapid cooling from above the critical temperature, as in usual heat treatment, is effective in improving low-temperature properties. As chromium steels have relatively high hardening capacity it was to be anticipated that chromium alone would help to raise the impact strength at low temperatures, and this has been found to be true, in the temperature ranges encountered under atmospheric conditions in automobiles, railways, and aircraft as well as in chemical processes such as dewaxing of oil.

Available data indicate that at elevated temperatures small amounts of chromium have a relatively slight effect on the properties except possibly in the case of high-carbon steels when some increased strength apparently results from the chromium.

78. Mechanical Properties at Low Temperatures.—The work on the effect of chromium on low-temperature properties reviewed hereafter was carried out before the importance of grain size was appreciated. However, in most cases the steels were made by identical processes so that the comparison may be considered valid.

Sergeson[375] tested chromium steels in the carburized and hardened condition such as would be used in gears. Unnotched Charpy specimens, 0.394 in. square, were carburized, water quenched, tempered at 150°C. (300°F.) to a hardness of about 60 Rockwell *C*, and tested at temperatures of 100 to −57°C. (212 to −70°F.). Results were as follows:

Composition, per cent			Charpy impact value, ft-lb., for a testing temperature of				
C	Cr	Mn	100°C. (212°F.)	24°C. (75°F.)	0°C (32°F.)	−27°C. (−16°F.)	−57°C (−70°F.)
0 15	1 35	0 46	26	.	.	18	12
0 15	0 74	0 53		12	8	7	5

It will be noted that the higher chromium steel gave decidedly superior impact strength. Spring steels, after oil hardening and tempering to 387 Brinell, were tested in the Charpy machine using specimens 0.394 in. square with an Izod notch. Results were:

Composition, per cent			Charpy impact value, ft-lb., for a testing temperature of			
C	Cr	Mn	107°C. (225°F.)	24°C. (75°F.)	0°C. (32°F.)	−32°C. (−25°F.)
0.50	1 00	0.70	24	19	17	16

Unnotched Charpy specimens, 0.250 × 0.395 in., were oil hardened and tempered at 455°C. (850°F.) to give a hardness of 418 Brinell. The low-temperature impact strength was as follows:

Composition, per cent				Charpy impact value, ft-lb., for a testing temperature of					
C	Cr	Mn	Si	100°C (212°F)	66°C (150°F)	24°C (75°F)	−11°C (12°F)	−26°C. (−15°F.)	−46°C. (−50°F)
0 49	1 14	0 85	0 15	90	76	74	94	96	74

Egan, Crafts, and Kinzel[385] made Izod tests on several chromium steels after normalizing (½-in. square bars) with the following results:

Composition, per cent				Approximate tensile strength, lb/sq. in.	Izod impact value, ft-lb, for a testing temperature of			
C	Cr	Mn	Si		25°C (77°F)	−50°C (−58°F)	−80°C (−112°F)	−183°C (−297°F)
0 25 to 0 35	0 80 to 1 10	0 60 to 0 90	0 15 minimum	85,000	33 0	4 3	3 8	1 8
0 25	2 89	0.69	0 25	185,000	18 0	12 0	9 0	3 5

It is apparent that chromium increases the low-temperature impact strength somewhat, but the investigators found that, in order to obtain a major degree of improvement, a carbide-forming element such as chromium should be combined with an austenite-forming element such as copper or manganese.

The plain chromium steels are seldom used where low-temperature toughness is a primary necessity, but chromium in combination with another alloy is used in steels for such applications. The moderate degree of low-temperature impact strength conferred by chromium permits plain chromium steels to be used where moderately low temperatures are encountered and where properties other than impact strength are more significant, as in rails and springs.

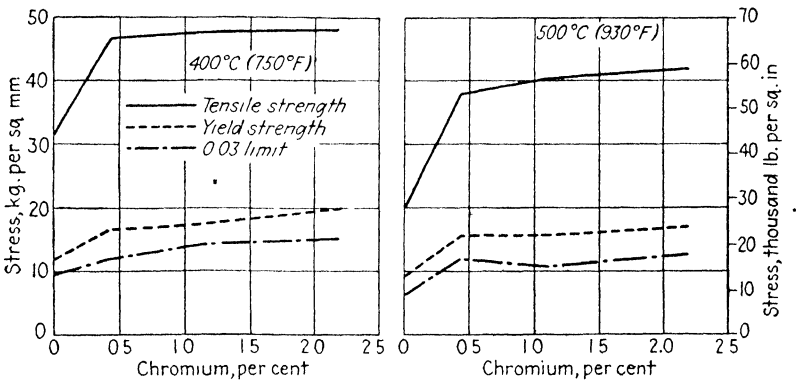


FIG. 88.—Effect of chromium on the tensile properties at elevated temperatures of a 0.1 per cent carbon steel. (*Grün.*[422])

79. High-temperature Strength.—Short-time tensile tests have been carried out at 400 and 500°C. (750 and 930°F.) by Grün[422] on steels containing up to 2.2 per cent chromium. The steels also contained about 0.1 per cent carbon, 0.5 per cent manganese, and some contained 0.1 per cent molybdenum. As shown in Fig. 88, chromium conferred a slight strengthening effect. The results of tests to determine a creep rate of 0.0005 per cent per hour between the 25th and 35th hour of test are also shown.

Spooner and Foley[346] reported the creep data of a 0.45 per cent carbon, 1.00 per cent chromium steel tested at 450°C. (840°F.). After annealing at 800°C. (1470°F.) the stress producing 1 per cent creep in 100,000 hr. was 6000 lb. per sq. in. After oil quenching from 825°C. (1515°F.), tempering, and oil quenching

from 650°C. (1200°F.) and again tempering at 425°C. (795°F.) followed by cooling in the furnace, the steel showed a stress of 7000 lb. per sq. in. for a creep rate of 1 per cent in 100,000 hr.

It is apparent from the above that small amounts of chromium alone have only a relatively slight effect on the high-temperature strength. With high carbon contents some increased strength results from small additions of chromium, but the primary high-temperature application for low-chromium steel lies in the range of 200 to 400°C. (390 to 750°F.) where relatively low stresses are encountered. Under these conditions the effect of chromium is to retard the annealing effect rather than to contribute a true increase in strength. In this connection, chromium steels have been used for many purposes such as rolls, dies, etc., where they seem to have a specific resistance to heat checking.

E. MECHANICAL PROPERTIES OF LOW-CHROMIUM CAST STEELS

Chromium is used in steel castings for many of the same reasons for which it is used in rolled and forged products. It confers high strength and wear resistance with simple heat treatments that require no more than normal foundry heat-treating equipment. According to Frank,[212] the steels are relatively free from tendency to distortion and have no abnormal shrinkage characteristics. The tendency of chromium to reduce ingotism assists in the avoidance of large dendritic grain size and resulting hot checking. In general, chromium-steel castings are used in applications requiring moderately high strength or particularly good wear resistance. Some improvement in corrosion resistance is produced, and the depth-hardening properties of chromium steels permit complex heat treatment if it is desired. The steels are used for frames and fittings on rolling equipment to reduce weight, in high-pressure valves and fittings for high strength, in car wheels, in excavating and conveying equipment to reduce wear, in heavy rolls and dies for resistance to wear and heat checking, and in many other applications requiring similar properties.

80. Mechanical Properties at Normal Temperature.—The mechanical properties of a number of low-chromium cast steels after various heat treatments have been reported by several investigators. These data are summarized in Table 51.

TABLE 51 —MECHANICAL PROPERTIES OF LOW-CHROMIUM CAST STEELS

Investigator	Composition, per cent				First treatment			Second treatment			Tempering temperature		Tensile strength, lb /sq in	Yield strength, lb./sq in	Elongation in 2 in , per cent	Reduction of area, per cent	Brinell hardness	Izod impact, ft-lb.
	C	Cr	Mn	Si	°C	°F	Cooled in	°C	°F	Cooled in	°C	°F						
Barton[102]	0 60 to 0 70	0 50 to 0 75			815	1500	? ? ?				425 565 705	800 1050 1300	114,000 100,600 79,000	103,400 94,300 64,500	14 3 20.1 34 4	54 4 60 0 66.6		
Meissner[226]	0 43	0 89	0 56	0 13	900	1650	Air				595	1100	102,000	68,000	14 0	18 0	174	9 0
	0 59	0 82	0 83	0 35	900	1650	Air				595	1100	132,000	73,000	12 0	13 0	255	3 0
	0 70	0 79	0 64	0 39	900	1650	Air				595	1100	128,000	89,000	3 0	3 0	269	3 0
Zuege[264]	0 35	0 77	0.67	0 37	900	1650	Air				675	1245	97,000*	56,000	17.5	26 0	207	
	0 38	0 81	0 74	0 50	900	1650	Air				675	1245	97,000	55,000	19 0	30 0	217	
	0 42	0 94	0 74	0 40	900	1650	Air				675	1245	91,000	51,000	18 0	25 5	212	
	0 45	0 68	0 82	0 50	900	1650	Air				675	1245	96,000	55,000	18 0	26 0	201	
	0 39	0 79	0 84	0 48	900	1650	Air	840	1545	Air			121,000†	74,000	8 5	12 6	241	
										Air	370	700	123,000	78,000	13 5	20 0	228	
										Air	650	1200	111,000	67,000	17.0	25 0	217	
										Oil	370	700	194,000	156,000	3 5	3 5	418	
										Oil	480	900	164,000	143,000	8 5	14 1	340	
										Oil	650	1200	120,000	90,000	16 0	35 7	241	
										Oil	735	1355	100,000	73,000	19 5	40 4	207	
Grotts[361]	0 36	0 83	0 74	0 41	900	1650	Air				675	1250	95,000	55,000	18.0	31 0	213	29 0
Lorig and Williams[368] ..	0 36	3 00	0 41	0 23	900	1650	Oil				595	1100	147,000	110,000	10.0	29.9	280	
Critchett[384] .	0 26	0 65	0 90	0 68	900	1650	Air	845	1550	Air			84,000	51,000	33 0	63 0		
	0 38	0 81	0 74	0 50	900	1650	Air				675	1250	97,000	55,000	19 0	30 0		
	0 36	3 00	0 41	0 23	900	1650	Air				675	1250	118,000	94,000	23	51		
	0 36	2 97	0 78		900	1650	Water				620	1150	151,000	127,000	14	29		
					870	1600	Oil				620	1150	142,000	122,000	15	34		
					815	1500	Oil				595	1100	138,000	120,000	16	37		

* Size of specimen 1 in × 1 in × 6 in
† Size of specimen ¾ in in diameter × 6 in.

A steel containing 0.45 per cent carbon, 1.5 per cent chromium, 0.49 per cent manganese, and 0.37 per cent silicon was tested by Rys,[299] after oil quenching and air cooling from 890°C. (1635°F.), in sections 20 to 400 mm. (0.79 to 15.75 in.) square. As shown in Fig. 89, there was some loss of impact strength in sections larger than 120 mm. (4.72 in.) square, and loss of tensile strength in sections larger than 200 mm. (7.86 in.) square.

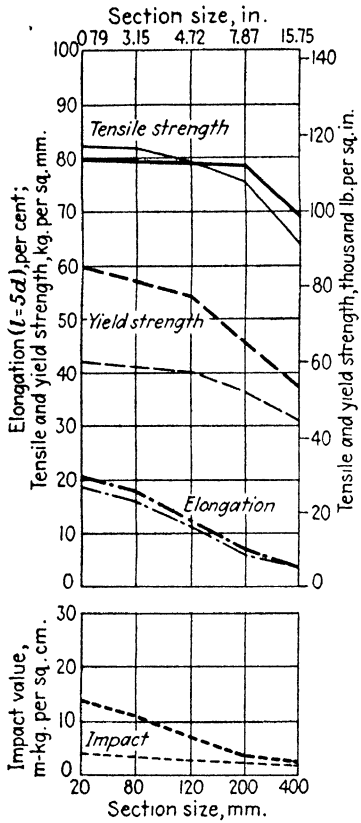


FIG. 89.—Effect of section size on the mechanical properties of a cast 0.45 per cent carbon, 1.50 per cent chromium steel. The values indicated by heavy lines were obtained after oil quenching, the ones indicated by light lines, after air cooling. All specimens were taken from the center. (*Rys.*[299])

81. Mechanical Properties at Elevated Temperatures.—The properties of a series of cast alloy steels, including one containing 2 per cent chromium, were determined by Müller and Piwowarsky[339] at temperatures up to 500°C. (930°F.). As shown in Figs. 90 and 91, the hardness, short-time tensile, and creep values approached those of carbon steel only at high temperatures. The impact strength reached a maximum at 300°C. (570°F.) and decreased somewhat at higher temperatures. The impact tests were made with a Charpy machine, the tensile tests were made at a rate of 15 mm. (0.59 in.) per min. after holding for 30 min. at temperature, and the "creep" was determined as the stress producing 0.003 per cent elongation per hour over a period of 10 to 15 hr.

F. MISCELLANEOUS PROPERTIES

There are relatively few data available on the miscellaneous properties of the low-chromium engineering steels. Except for

the papers of Hadfield[19] in 1892 and Benedicks[29] in 1904, nearly all the important data on density, coefficient of expansion, thermal conductivity, thermal electromotive force, electric resistance, corrosion resistance, and wear resistance have been

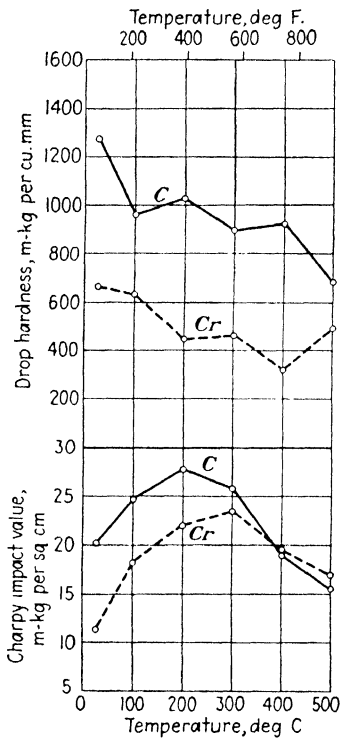


FIG. 90.—Effect of temperature on hardness and impact properties of a cast steel containing 0.18 per cent carbon, 0.47 per cent silicon, 0.87 per cent manganese, 0.042 per cent phosphorus, and 2.12 per cent chromium, compared with a 0.12 per cent carbon cast steel.

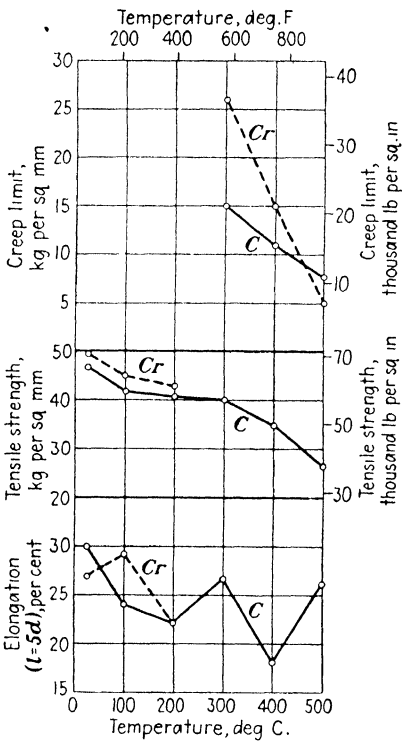


FIG. 91.—Effect of temperature on the tensile properties of the steels described in Fig. 90. The chromium steel was annealed at 880°C. (1615°F), the carbon steel 930°C. (1705°F.). (*Müller and Piwowarsky.*[339])

reported in the past 20 years. These few data are correlated in the present section.

Of the 19 investigations of the miscellaneous properties of low-chromium steels which are reviewed hereafter, 11 are on density and electric resistance. It is evident, therefore, that there are few data on the other properties; moreover, most of the

values reported were determined on chromium steels of certain compositions and heat treatments and do not show clearly the effect of chromium on the property in question.

82. Density.—The density of chromium steels containing the small amounts of other elements common in steel has been determined after various heat treatments. In the annealed and quenched and fully tempered conditions the following relations have been found for the effect of small amounts of chromium on the specific volume of iron:

According to Benedicks[29] ..... 0.1274 + 0.000165 Cr
According to Dickie[239] as calculated by Greaves . 0 12712 + 0 0002 Cr
According to Greaves[449] ..... 0 1270 + 0.0002 Cr

In these formulas the first figure is the specific volume of iron. The second figure, when multiplied by the percentage of chromium, gives the amount of increase in specific volume caused by the chromium.

TABLE 52.—DENSITY AND SPECIFIC VOLUME OF LOW-CHROMIUM STEEL

Investigator	Specimen No.	Composition, per cent				Specific volume		Density
		C	Cr	Mn	Si			
Andrew, Fisher, and Robertson[151,175]	1	0 35	1 56	0 24	0 17	0 12765		7 834
	2	0 62	1 67	0 22	0 18	0 12786		7 821
	3	0 80	1 67	0 28	0 20	0.12793		7 817
	4	0 98	1 68	0 28	0 22	0 12802		7.811
	5	1 73	1 65	0 30	0 21	0 12823		7 798
						(*A*)	(*B*)	
Dickie[239] . . .	11	0 31	1 00	0 74	0 13	0 127627	0.127622	
	12	0.20	1 85	0 14	0 05	0 127568	0 127556	
	13	0 22	2 80	0 10	0 08	0 127822	0 127793	
	14	0 21	3 88	0 19	0.10	0 128033	0 128047	
	15	0 30	5.54	0 08	0.12	0 128401	0 128373	

Values for the specific volume of low-chromium steels of various carbon and chromium contents are given in Table 52. The steels used by Andrew, Fisher, and Robertson[151,175] were in the annealed condition; the steels used by Dickie[239] had been heat

treated as follows: (*A*) quenched in oil from 900°C. (1650°F.) and tempered at 750°C. (1380°F.) followed by quenching in water; and (*B*) quenched in oil from 900°C. (1650°F.) and tempered at 750°C. (1380°F.) followed by quenching in water and retempering at 500°C. (930°F.). Steel 11 was tempered at 735°C. (1355°F.) instead of 750°C. (1380°F.).

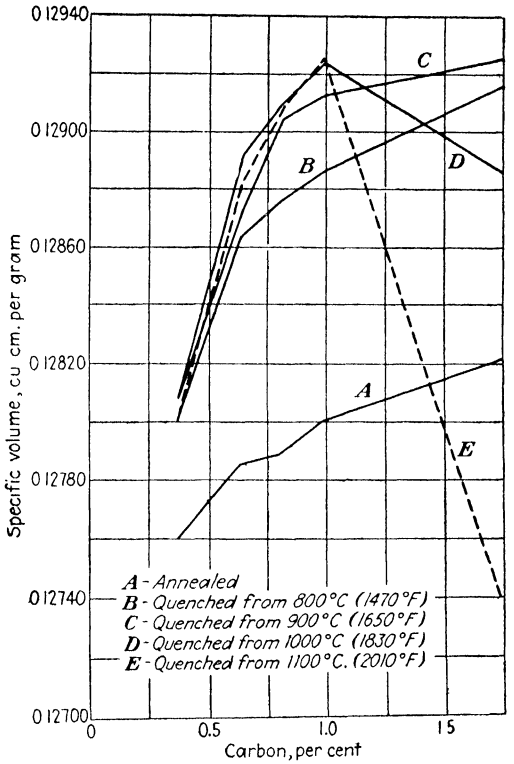


FIG. 92.—Effect of quenching on the specific volume of 1.6 per cent chromium steels of different carbon content. (*Andrew, Fisher, and Robertson.*[151])

Andrew, Fisher, and Robertson also investigated the effect of quenching temperature on the specific volume of the steels whose analyses are given in Table 52 and their specific volume after quenching from 1100°C. (2010°F.) and tempering at various temperatures. These data are plotted in Figs. 92 and 93. While tempering the 0.35 per cent carbon steel produced a continuous decrease in specific volume, higher carbon steels showed martensite decomposition with tempering temperatures

up to 200°C. (390°F.), austenite transformation from 200 to 300°C. (390 to 570°F.), and further martensite decomposition at temperatures above 300°C.

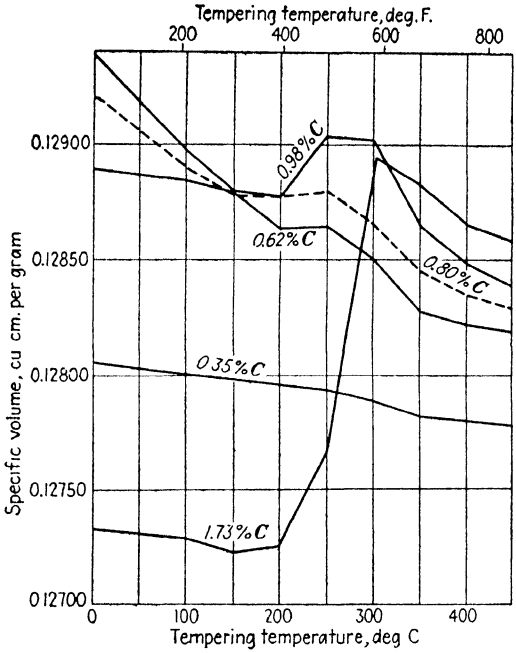


FIG. 93.—Effect of tempering on the specific volume of 1.6 per cent chromium steels of different carbon content, quenched from 1100°C. (2010°F.). (*Andrew, Fisher, and Robertson.*[151])

An investigation by Heindlhofer and Wright[159] on hardened steel balls confirmed these findings. Balls of the following analysis were quenched in water and oil and tempered:

Diameter of ball, in.	Composition, per cent			
	C	Cr	Mn	Si
½	1 06	0 71	0 40	0 32
9/16	0.98	0 55	0.25	0 27

As shown in Fig. 94, decomposition of martensite produced an increase in density with tempering temperatures up to 200°C. (390°F.). From 200 to 260°C. (390 to 500°F.) austenite was

transformed with decrease of density, and at higher temperatures further increase in density occurred. The presence of austenite was confirmed by X-ray examination. Although the martensitic

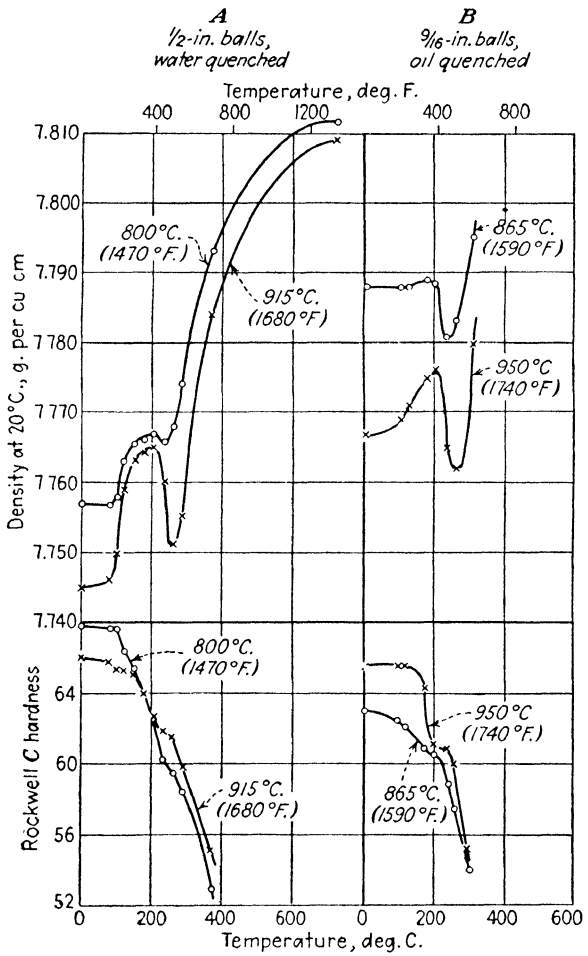


FIG. 94.—Effect of tempering on the density and hardness of ½-in. and 9/16-in. diameter chromium-steel balls, quenched from the indicated temperatures in water and in oil. (*Heindlhofer and Wright.*[159])

needle structure disappeared at 300°C. (570°F.) the increase in density due to tempering of martensite appeared to be continuous. Styri in a discussion of this paper showed similar results obtained by dilatometric methods on chromium-steel balls.

83. Coefficient of Expansion.—Linear-expansion data on plain chromium steels have been determined, usually with some specific purpose in mind. Matsushita[88] determined the coefficient of expansion of a graded series of chromium steels containing 0.6 per cent carbon to be as follows:

Chromium, per cent	Coefficient of expansion $\times 10^6$, per °C.	
	At 100°C.	At 500°C.
0	11 5	15 9
0 5	11 9	15 6
1 0	11 3	14 8
2 0	11 8	14 3
3 0	12 1	14 8

Mochel[337] reported the coefficients of annealed steels containing 0.95 to 1.10 per cent carbon, under 0.40 per cent manganese, and 1.30 to 1.50 per cent chromium to be:

Temperature range, °C.	Coefficient of expansion $\times 10^6$, per °C.
0 to 100	12 2
0 to 200	12 7
0 to 300	13 2
0 to 400	13 8
0 to 500	14 3

The values given in Table 53 were assembled by Hidnert[327] from various sources.

It is apparent from the available data that chromium in the amounts under consideration has little effect on the coefficient of expansion. As Hidnert's table includes several steels containing alloys other than chromium, the effect of other alloy additions also appears to be very small and will not be further discussed.

84. Thermal Conductivity.—While the thermal conductivity of the higher chromium steels has received a good deal of attention, little study has been made of this property in low-chromium

TABLE 53.—AVERAGE COEFFICIENTS OF EXPANSION OF LOW-CHROMIUM STEELS*

Composition, per cent		Treatment	Average coefficients of expansion × 10^6, per °C.						
C	Cr		Room to 100°C.	Room to 200°C.	Room to 300°C.	Room to 400°C	Room to 500°C.	Room to 600°C.	Room to 700°C.
1 28	0 19	Annealed	11 0		12 0			14.1	
0 36	0 57	Annealed	11 8	12 3	13 1	13 6	14 1	14.5	14 9
0 40	0 78	Quenched and tempered	12 8	13 4					
0 34	0 82	Annealed	11 6	12 1	12 9	13 7	14 2	14 6	14 9
0 12	0 85	Annealed	11 6	12 1	12 7	13 2	13 6	14 0	14 3
0 17	0 92	Annealed	11 3	11 6	12 5	13 2	13 7	14 2	14 5
0 34	0 96	Quenched and tempered	11 8	12 7					
0 35	1 00	Annealed	12 4	12 6	13 3	13 8	14 2	14 5	14 7
0 14	1 15	Annealed	11 2	12 0	12 7	13 5	13 9	14 3	14 6
0 35	1 17	Annealed	11 0	11 8	12 9	13 6	14 1	14 5	14 7
0 40	1 20	Quenched and tempered	11 6	12 4					

* Hidnert (327)

steels. It would appear from work on the higher chromium steels that chromium causes a drop in thermal conductivity, but the major part of the drop seems to occur in compositions containing over 3 per cent chromium. This is shown to some extent by the work of Matsushita(88) on 0.6 per cent carbon steel as follows:

Chromium, per cent	Conductivity, cal. per sec. per sq. cm. (°C. per cm.)	
	Annealed at 900°C.	Quenched from 1100°C.
Nil	0 100	0 0981
0 5	0 0995	0 0886
1 0	0 0960	0 0882
2.0	0 0955	0 0870
3 0	0 0895	0 0575

85. Thermal Electromotive Force.—Only one paper has been found on the effect of chromium on thermal electromotive force.

Dupuy and Portevin[61] carried out tests with steel against copper which showed that, in amounts up to 3.5 per cent chromium, the thermal electromotive force is increased by chromium. This is shown in Table 54.

TABLE 54.—THERMAL ELECTROMOTIVE FORCE (MICROVOLTS PER °C.) OF CHROMIUM STEEL VERSUS THE METAL COPPER*

Steel No.	Composition, per cent				As rolled		Annealed at 1000°C.		Water quenched at 1000°C.	
	C	Cr	Mn	Si	−80°C	+100°C	−80°C	+100°C	−80°C	+100°C
1C1	0 06	1 20	Trace	0 70	+17 1	+16 6	+17 53	+16 93	+ 6 70	16 40
1C2	0 08	1 89	0 08	0 12	15 2	16 6	15 43	16 65	14 50	15 20
1C3	0 28	2 66	0 15	0 05	14 7	17 1	16 94	18 11	14 60	21 50
8C1	0 97	0 92	0 24	0 22	9 51	8 83	9 74	8 92	3 90	3 64
8C2	0 89	2 14	0 10	0 28	9 51	9 00	10 21	9 64	3 52	4 20

* Dupuy and Portevin.[61]

86. Electric Resistance.—Early work by Portevin[47] on Guillet's annealed steels indicated, in the low-chromium ranges, an increase of 5.4 microhms for 1 per cent chromium in the 0.20 per cent carbon series, and of 8 microhms for 1 per cent chromium in the 0.80 per cent carbon series. In quenched steels the resistance was found to increase rapidly up to 2 per cent chromium. These results have been modified in the light of more recent work (Table 55), but the same general tendencies have been found. Other early work on chromium steels was carried out by Hopkinson, LeChatelier, Barrett, Brown, and Hadfield, Boudouard, and Murakami. Their results are not of present interest and have been summarized by Edwards and Norbury[83] in their broad study of the effect of chromium on electric resistance.

The last-named investigators found that chromium produced little, if any, change in resistance until the ratio of chromium to carbon exceeded 4.3 to 1. From this they deduced the presence of a double carbide, $Fe_3C.Cr_3C_2$. Resistivity was measured after normalizing and quenching from different temperatures and after subsequent tempering of normalized specimens. Typical results on a 2 per cent chromium steel with medium and high carbon are given in Table 55.

TABLE 55.—ELECTRIC RESISTANCE OF ANNEALED, NORMALIZED, QUENCHED, AND TEMPERED LOW-CHROMIUM STEELS*

Steel No.	Composition, per cent				Electric resistivity, microhms per cu. cm.								
					Annealed,† resistivity	Normalized			Quenched in water			Tempered‡		
						Temperature		Resistivity	Temperature		Resistivity	Temperature		Resistivity
	C	Cr	Mn	Si		°C.	°F.		°C.	°F		°C.	°F.	
1	0 33	1.96	0 13	0 05	17 83	920	1690	21 74	815	1500	17 91	150	300	22 13
						950	1740	22 69	960	1760	25 23	210	410	21.78
						1000	1830	22 41	1300	2370	25 14	250	480	21 82
						1170	2140	22 30	....	...	..	300	570	21 52
						1300	2370	22 83						
2	0 87	2 08	0 19	0.18	18 31	900	1650	39 16	805	1480	29 85	180	360	35.34
						950	1740	41 02	960	1760	44 21	220	430	31 31
						1000	1830	41 12	1170	2140	44 72	305	580	29 39
						1170	2140	42 07	1300	2370	44 74	460	860	27 52
						1300	2370	41.05			...	540	1000	21 61
						.	.		.	.	. .	640	1180	19.19
3	1 00	2 09	0 29	0 17	18 78	900	1650	36 68	805	1480	31 37			
						950	1740	35 92	960	1760	48.17			
						1000	1830	44 51	1170	2140	49 34			
						1170	2140	48 75	1300	2370	49 27			
						1300	2370	47 97						
4	1 26	2.11	0 20	0 18	18 92	900	1650	24 08	805	1480	35 58			
						950	1740	35 41	960	1760	50 08			
						1000	1830	29 31	1170	2140	54 03			
						1170	2140	53 14	1300	2370	54 19			
						1300	2370	51 11						
5	0.28	1 03	0 28	0 03	17 10									
6	0 56	1.12	0 55	0 20	19 94									
7	1 81	2.10	0 37	0 12	22 14									
8	0 38	2 94	0 32	0 08	20 51									

* Edwards and Norbury.[83]

† Annealing temperature not given

‡ Normalized at 910°C. (1670°F) (Steel 1) and 900°C. (1650°F.) (Steel 2) before tempering.

Electric resistivity was also determined by Matsushita[88] on steels containing 0.6 per cent carbon and varying chromium, by Campbell and Whitney[135] on a series of alloys in which the carbon was varied by carburizing or decarburizing, and by

TABLE 56.—ELECTRIC RESISTANCE OF ANNEALED, QUENCHED, AND TEMPERED LOW-CHROMIUM STEELS

Investigator	Steel No.	Composition, per cent				Electric resistivity, microhms per cu. cm.									
						Annealed			Quenched				Tempered		
						Temperature		Resistivity	Temperature		Quenching medium	Resistivity	Temperature		Resistivity
		C	Cr	Mn	Si	°C	°F.		°C.	°F.			°C.	°F.	
Matsushita[88]	1	0 6	0 0	....	....	900	1650	20.7	1100	2010	*	20 7			
	2	0 6	0 5	....	....	900	1650	22 0	1100	2010	*	22.4			
	3	0 6	1 0	....	....	900	1650	21 9	1100	2010	*	22 8			
	4	0 6	2.0	....	....	900	1650	21 1	1100	2010	*	22 9			
	5	0 6	3 0	....	.. .	900	1650	25 6	1100	2010	*	35.5			
Campbell and Whitney[135]	11	0 04	2 23	0 24	0 25	*	*	29 19	900	1650	Oil	30 04			
	12	0 36	2 23	0 24	0 25	*	*	26 21	900	1650	Oil	34 12			
	13	0 50	2 23	0 24	0 25	*	*	25 03	900	1650	Oil	38 12			
	14	0 85	2 23	0 24	0 25	*	*	23 79	900	1650	Oil	43 81			
	15	1 05	2 23	0 24	0 25	*	*	25 99	900	1650	Oil	48.91			
	16	1 43	2 23	0 24	0 25	*	*	27 03	900	1650	Oil	50 31			
	17	1 62	2 23	0 24	0 25	*	*	27 72	900	1650	Oil	52 09			
Messkin and Towpenjez[171]	..	1 33	2 15	0 55	0 37	.			850†	1560†	Oil	.	100	210	47 0
													200	390	44 0
													300	570	38 0
													400	750	37 0
													500	930	36 5
													550	1020	32 0
													600	1110	30 0

* Not given

† Previously normalized at 1000°C (1830°F.).

Messkin and Towpenjez[371] on a 1.33 per cent carbon, 2.15 per cent chromium magnet steel which had been normalized at 1000°C. (1830°F.), oil quenched from 850°C. (1560°F.), and tempered at various temperatures. The results of these investigators are given in Table 56.

Dickie[239] determined the specific resistance of 4 of the steels which he used for density determination (see Table 52, page 202, for composition and text, page 203, for description of treatment). The results were as follows:

Steel No.	Composition, per cent		Specific resistance at 20°C. (70°F.), microhms per cu. cm.	
	C	Cr	Treatment *A*	Treatment *B*
11	0 31	1.00	20 52	20 12
12	0 20	1 85	18 65	19 09
13	0 22	2 80	22 15	22 09
14	0 21	3.88	26 23	26 46

While it is apparent that chromium increases the electric resistivity and some attempts have been made to evaluate the amount, the relation among chromium, iron, and their carbides is so complex that no rational formula has been developed. With the better understanding of the complex carbides, it is to be anticipated that such an analysis will be carried out in the near future.

87. Corrosion Resistance.—Until recent years, low-chromium steels were not used to any great extent for structural purposes where corrosion resistance was significant, hence there have been only a limited number of tests carried out to show the specific effect of small amounts of chromium. Furthermore, the chromium-bearing structural steels are mainly of the complex types and data on these are reviewed in Chapters VIII and IX.

Hadfield[19] determined the rate of solution in 50 per cent H_2SO_4 and found that a small amount of chromium retarded the attack somewhat. Friend, Bentley, and West[53,55] reported the corrodibility of two chromium steels and, for comparison, of a plain carbon steel. The three steels had the following composition:

Steel	Composition, per cent			
	C	Cr	Mn	Si
A	0 29	....	0 39	0.14
B	0 32	1 12	0 36	
C	0.11	3.58	0 11	

Results are given in Table 57. The tests showed a tendency

TABLE 57.—CORROSION FACTORS OF CARBON AND CHROMIUM STEELS IN VARIOUS MEDIA*

Corroding medium	Exposure, months	Corrosion factor for		
		Steel *A*	Steel *B*	Steel *C*
Tap water	2	100	85	58
	6	100	73	61
Sea water	2	100	60	26
	6	100	80	40
Wet and dry....	2	100	93	30
	6	100	109	25
0.05 per cent H_2SO_4.. .	2	100	71	68
	6	100	89	102
0.5 per cent H_2SO_4...	2	100	223	61
Hot water ...	1	100	100	64

* Friend, West, and Bentley.[65]

toward greater corrosion resistance for the chromium steels that agrees with more recent experience. However, corrodibility is subject to so many factors that finely drawn conclusions are not justified from this investigation.

Endo[211] determined the relative weight loss of a 2.42 per cent chromium steel in acids as follows:

Composition, per cent		Weight loss in 5 hr., g. per sq. cm.		
C	Cr	5 per cent H_2SO_4	5 per cent HCl	5 per cent HNO_3
0.31	...	0 00270	0 00210	0 08079
0.3	2.42	0.00490	0.00541	0 04736

Although low-chromium steels have a slightly increased corrosion resistance in aqueous media, they are used primarily for resistance to atmospheric corrosion as they tend to build up a fine-grained rust that adheres fairly well and offers a certain degree of protection. In addition, it has been generally observed that the relatively tight scale of chromium steels offers a better surface so that the bare corrosion rate is lower and protective paints have less tendency to peel than with carbon steels. This is of particular importance in places where erosion is encountered as in running water and in chutes, hoppers, and the like. It is also probable that a part of the high capacity of chromium steels for wear resistance is due to reduced corrosion.

88. Wear Resistance.—Few reliable data on wear resistance of chromium steel have been published in spite of the fact that many applications of chromium steel are based on this quality. In the strictly structural and engineering medium-carbon, low-chromium steels the increase in wear resistance seems to be relatively slight. In high-carbon grades, ball bearings are made almost wholly from chromium steel, and the chromium tool steels find a specific application in uses where wear is a major factor, as in shear blades and punching dies. The same is true of carburized steels with 3 per cent chromium. The increased resistance to wear is quite appreciable. Products such as railroad rails show exceedingly little wear.[441] Although it has been demonstrated many times that chromium steels have superior wear resistance in certain applications, the factors determining this property are not sufficiently well known to justify any broad conclusions regarding the mechanism of the effect of chromium on wear resistance, although the presence of chromium carbides may well be a dominant factor together with increased corrosion resistance discussed in the previous section.

G. INDUSTRIAL APPLICATION OF LOW-CHROMIUM STEELS

There are three grades of plain low-chromium engineering and structural steels which are used extensively in industry. The composition ranges and the corresponding Society of Automotive Engineers[456] steel numbers are as given in Table 58. In addition to these, S.A.E. steel 5135 is occasionally used in the normalized condition for automotive parts, and a steel corresponding to

S.A.E. 5150 has been used experimentally in the rolled condition for rails.

TABLE 58.—COMPOSITION AND GRADES OF S.A.E. LOW-CHROMIUM STEELS*

S.A.E. No.	Grade	Composition, per cent		
		C	Cr	Mn
5115	Carburizing	0.10 to 0.20	0.60 to 0.90	0.30 to 0.60
5120	Carburizing	0.15 to 0.25	0.60 to 0.90	0.30 to 0.60
5125	Water hardening	0.20 to 0.30	0.80 to 1.10	0.60 to 0.90
5135	Water hardening	0.30 to 0.40	0.80 to 1.10	0.60 to 0.90
5140	Oil hardening	0.35 to 0.45	0.80 to 1.10	0.60 to 0.90
5150	Oil hardening	0.45 to 0.55	0.80 to 1.10	0.60 to 0.90

* Society of Automotive Engineers.[456]

89. Plain Chromium Carburizing Steel.—Steel with less than 0.25 per cent carbon and from 0.50 to 1.00 per cent chromium has been widely used for case-hardened parts. The addition of chromium permits the use of lower carbon content without sacrifice of satisfactory core properties. Chromium accelerates the rate of hardening and increases the surface hardness. That the depth-hardening capacity and tendency toward "normality" in chromium steel permit the steel to oil harden with little distortion and greater homogeneity is common experience. Unless the steel has been made to retain a certain grain size during carburizing, parts should be given a double heat treatment for toughening the core and hardening the case. The heat treatments recommended by the Society of Automotive Engineers are as follows for S.A.E. steel 5120:

Heat treatment No. 1:

1. Normalize at least 30°C. (50°F.) above carburizing temperature.
2. Carburize at 900 to 925°C. (1650 to 1700°F.).
3. Quench direct from carburizing box.
4. Reheat to 775 to 800°C. (1425 to 1475°F.) for case hardness only, or reheat to 800 to 830°C. (1475 to 1525°F.) for core hardness.
5. Quench in oil.
6. Temper at 120 to 150°C. (250 to 300°F.).

Heat treatment No. 2:

1. Normalize at least 30°C. (50°F.) above carburizing temperature.

2. Carburize at 900 to 925°F. (1650 to 1700°F.).
3. Cool slowly or in carburizing box.
4. Reheat to 775 to 800°C. (1425 to 1475°F.) for case hardness only, or reheat to 800 to 830°C. (1475 to 1525°F.) for core hardness.
5. Quench in oil.
6. Temper at 120 to 150°C. (250 to 300°F.).

Heat treatment No. 3:

1. Normalize at least 30°C. (50°F.) above carburizing temperature.
2. Carburize at 900 to 925°C. (1650 to 1700°F.).
3. Cool slowly or in carburizing box.
4. Reheat to 870 to 900°C. (1600 to 1650°F.).
5. Quench in oil.
6. Reheat to 775 to 800°C. (1425 to 1475°F.).
7. Quench in oil.
8. Temper at 120 to 150°C. (250 to 300°F.).

Heat treatment No. 4:

1. Heat to 815 to 900°C. (1500 to 1650°F.) in cyanide or activated bath.
2. Quench in oil or water.
3. Temper if desired.

Parts "cased" in activated baths may be given refining heats as indicated in preceding heat treatments.

The mechanical properties of the core of a chromium carburizing steel with 0.15 per cent carbon (S.A.E. 5115) depend upon the treatment. Tensile strengths which are frequently attained range from 85,000 to 125,000 lb. per sq. in., yield strengths from 60,000 to 100,000 lb. per sq. in., elongation in 2 in. from 15 to 20 per cent, and reduction of area from 35 to 60 per cent. The case is uniformly file hard and has the characteristic wear resistance of chromium steel. The S.A.E. 5120 steel is used for many carburized automotive, aircraft, and general machine parts such as roller bearings, wrist pins, cam shafts, small gears, and worms.

Much application has been made of higher chromium carburizing steels for special purposes, such as heavy gears, stamps, and dies. The parts are usually made of 2 per cent chromium steel and are carburized to a great depth.

90. Water-hardening Chromium Steels.— Steels with 0.25 to 0.40 per cent carbon and 0.80 to 1.10 per cent chromium—Nos. 5130 and 5135 in the S.A.E. series—are used for a variety of machine parts requiring tensile strength in the range of 100,000

to 150,000 lb. per sq. in. The required properties are developed by water quenching and tempering in the range 600 to 705°C. (1100 to 1300°F.). The effect of tempering on the tensile properties of such steels is shown in Fig. 95, for S.A.E. 5130, and in Fig. 96 for S.A.E. 5135 steel (see Table 59 for compositions and heat treatments). In moderate sections these steels have a high degree of ductility and impact strength and are ordinarily used

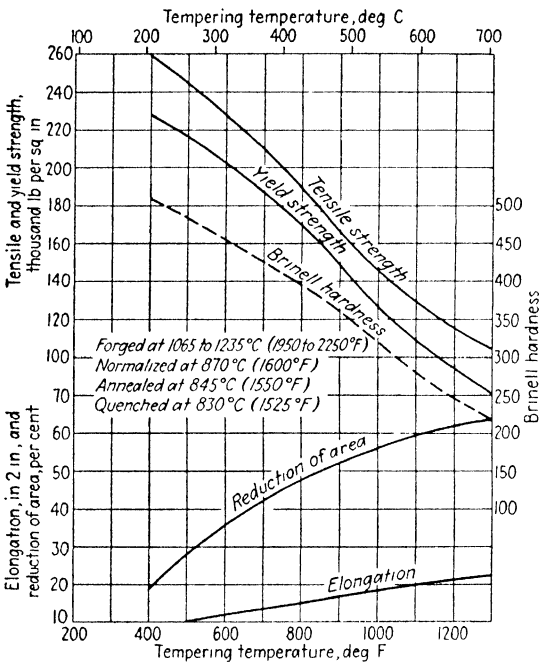


FIG. 95.—Effect of tempering on the tensile properties of a fine-grained water-quenched 0.30 per cent carbon, 1 per cent chromium steel (S.A.E. 5130), treated in the form of 1-in. round bars. (*Republic Steel Corporation*, 1935.)

in applications demanding these properties. In automotive work, they are used for front axles, steering knuckles, connecting rods, small gears, valve stems, and pump and drive shafts.

91. Oil-hardening Chromium Steels.—The 1 per cent chromium steels containing over 0.40 per cent carbon are usually hardened by quenching in oil. In automotive work two grades are used: S.A.E. 5140 and 5150 (see page 214 for composition).

The heat treatments recommended[456] for these steels are shown as follows:

Heat treatment No. 1 for steel 5140:

1. Normalize and anneal to desired structure for machinability.
2. Heat to 815 to 870°C. (1500 to 1600°F.).
3. Quench in oil.
4. Temper to desired hardness.

Heat treatment No. 2 for steel 5140 (for gears):

1. Normalize and anneal to desired structure for machinability.

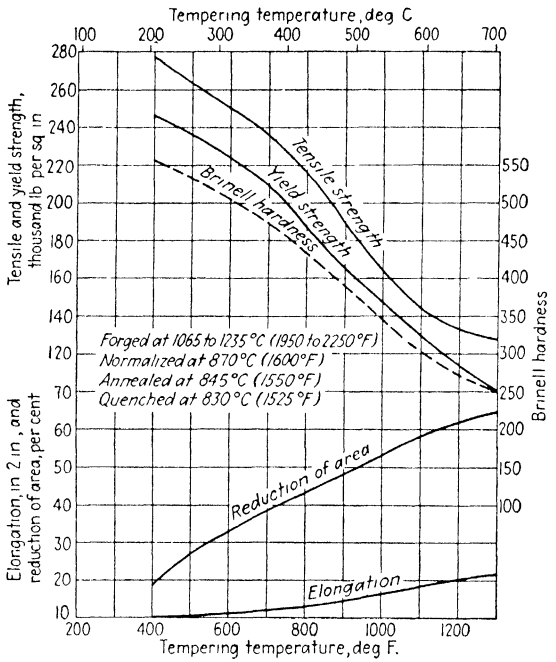


FIG. 96.—Effect of tempering on the tensile properties of a fine-grained water-quenched 0.35 per cent carbon, 1 per cent chromium steel (S.A.E. 5135), treated in the form of 1-in. round bars. (*Republic Steel Corporation*, 1935.)

2. Heat to 800 to 830°C. (1475 to 1525°F.) in cyanide or activated bath.
3. Quench in oil.
4. Temper at 190 to 230°C. (375 to 450°F.).

Heat treatment No. 1 for steel 5150:

1. Normalize and anneal to desired structure for machinability.
2. Heat to 790 to 845°C. (1450 to 1550°F.).
3. Quench in oil.
4. Temper to required hardness.

Heat treatment No. 2 for steel 5150 (for gears):

1. Normalize and anneal to desired structure for machinability.

TABLE 59.—COMPOSITIONS AND HEAT TREATMENTS OF STEELS WHOSE AVERAGE MECHANICAL PROPERTIES ARE GIVEN IN THE CHARTS*

Fig. No.	S.A.E. No.	Composition range,† per cent			Normalized, air cooled from		Annealed, furnace cooled from		Quenched in oil from		Critical points			
											Ac_1‡		Ac_3	
		C	Cr	Mn	°C.	°F.	°C.	°F.	°C.	°F.	°C.	°F.	°C.	°F.
95	5130	0 28 to 0 33	0 80 to 1 10	0 60 to 0 80	870	1600	845	1550	830	1525§	745	1370	800	1470
96	5135	0 33 to 0 38	0 80 to 1 10	0 70 to 0 90	870	1600	845	1550	830	1525§	740	1365	795	1460
97	5145	0 42 to 0 47	0 85 to 1.10	0 70 to 0 90	870	1600	830	1525	830	1525	740	1365	790	1450
98	5150	0 47 to 0.52	0.85 to 1 10	0 70 to 0 90	870	1600	830	1525	820	1510	740	1365	780	1440
99	5150	0 47 to 0.52	1 00 to 1 20	0 80 to 1 00	860	1575	830	1525	830	1525	720	1330	785	1445

* Republic Steel Corporation, 1935

† Maximum sulphur or phosphorus 0 04 per cent

‡ Ar_1 is given as 50 to 55°C. (90 to 100°F.) lower than Ac_1.

§ Quenched in water.

2. Heat to 800 to 830°C. (1475 to 1525°F.).
3. Quench in oil.
4. Temper at 190 to 220°C. (375 to 425°F.).

Typical average properties of steels included in the S.A.E. 5145 and S.A.E. 5150 specifications are shown in Figs. 97 and 98 (see Table 59 for compositions and heat treatments). The steels

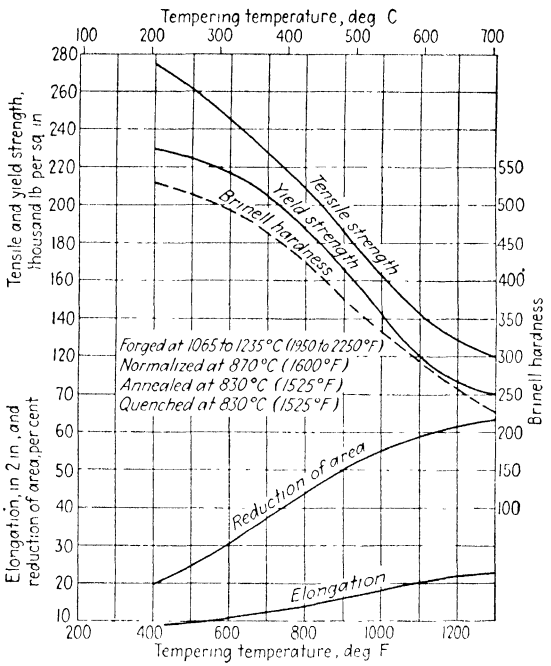


FIG. 97.—Effect of tempering on the tensile properties of a fine-grained oil-quenched 0.45 per cent carbon, 1 per cent chromium steel (S.A.E. 5145), treated in the form of 1-in. round bars (*Republic Steel Corporation*, 1935.)

are recommended for heat-treated forgings, shafts, and gears. They are heat treated by quenching in oil and tempering to suitable hardness. The greatest use for these steels is in gears where their high wear resistance can be utilized. They are also used for drive shafts and rear axles.

A steel similar to S.A.E. 5150, but usually with a slightly different composition, depending on application, is used for helical and laminated springs and lock nuts. Full hardening is realized on oil quenching, and the springs are usually tempered to a hard-

ness of about 400 Brinell. The composition and heat treatment are given in Table 59 and typical properties in Fig. 99.

High-carbon chromium steels are used in applications that approach the tool-steel class, which is discussed in Chapter X.

92. Air-hardening Chromium Steels.—Although this is not very common practice, a large number of automotive parts are

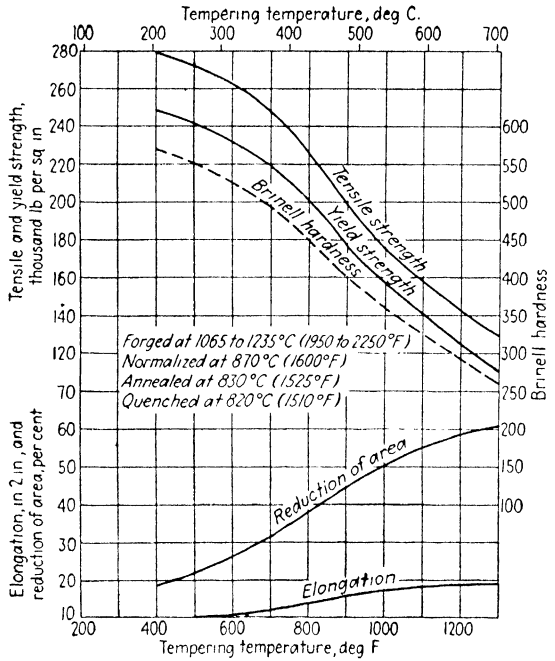


FIG. 98.—Effect of tempering on the tensile properties of a fine-grained oil-quenched 0.50 per cent carbon, 1 per cent chromium, 0.80 per cent manganese steel (S.A.E. 5150), treated in the form of 1-in. round bars. (*Republic Steel Corporation*, 1935.)

used in the normalized condition. As a rule, the S.A.E. grades corresponding closely to 5135 are used for this purpose. High ductility and impact strength result from this practice when the strength is not too high. The S.A.E. 5135 steel is air hardening and, in sections up to about 2 in. in diameter, normalizing is, therefore, an economical and safe method of heat treating for connecting rods, front axles, and steering arms.

Some use has been made of 1 per cent chromium steel for structural work in the form of plate and tubing. As a rule, the

strength is 90,000 lb. per sq. in. or less, and a carbon content of about 0.20 per cent is used. The greatest use of chromium in structural steel is in combination with other alloying elements. Such steels are discussed in Chapters VIII and IX.

93. Plain Chromium Steel Rails.—On account of their good properties in the rolled condition, chromium steels have been

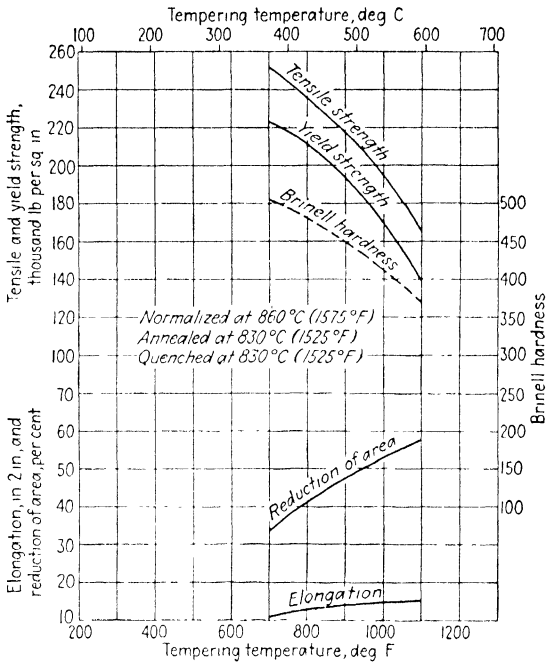


FIG. 99.—Effect of tempering on the tensile properties of a fine-grained oil-quenched 0.50 per cent carbon, 1.10 per cent chromium, 0.90 per cent manganese steel (S.A.E. 5150), treated in the form of 1-in. round bars. (*Republic Steel Corporation*, 1935.)

tested for use in railroad rails with interesting results. Swinden and Johnson[234] investigated the properties of rails containing 1 per cent chromium. Composition and properties are given in Table 60. Drop tests were satisfactory for both the acid Bessemer and the acid open-hearth rails. A length of heat *AB* (acid Bessemer) was heated to various temperatures and cooled in an air blast to determine the effect of heating at temperatures used in hot bending. The results (Table 60) indicated that this treatment has no marked effect on tensile properties.

TABLE 60.—COMPOSITION AND PROPERTIES OF 1 PER CENT CHROMIUM STEEL RAILS*

Heat No.	Composition, per cent				Heated to		Tensile strength, lb./sq. in.	Yield strength, lb /sq. in.	Elongation in 3 in., per cent	Reduction of area, per cent
	C	Cr	Mn	Si	°C.	°F.				
Acid Bessemer, 100-lb. rails, MR sections										
AB	0.51	1.02	0.84	0.21	..	..	135,000	..	8.0	11.6
BB	0.49	0.95	0.85	0.18	.		121,100	..	11.0	16.2
CB	0.52	0.99	0.88	0.21			136,200		9.0	14.0
Cooled in air blast										
AB	0.51	1.02	0.84	0.21	400	750	130,900		8.0	10.4
					500	930	137,200		8.5	11.6
					600	1110	135,700		8.5	11.6
					700	1290	133,800	.	11.0	19.2
					800	1470	137,500	.	10.5	20.8
Acid open-hearth, 90- and 95-lb. rails, RBS sections										
A	0.50	0.99	0.78	0.22	.		138,100	81,100	14.0	31.6
B	0.51	1.01	0.83	0.18			134,400	83,400	15.5	36.7
C	0.49	0.90	0.81	0.17			134,200	76,400	14.0	31.6
D	0.47	0.91	0.82	0.15			136,400	71,700	13.5	26.8
E	0.49	0.80	0.85	0.25			131,000	73,600	14.5	27.4
F	0.53	1.09	0.78	0.27			142,200	82,900	9.5	12.8
G	0.54	0.91	0.75	0.27		.	132,300	80,900	10.3	15.2
H	0.55	1.00	0.78	0.25			136,800	82,000	12.5	23.0
I	0.53	0.92	0.85	0.25			137,600	82,200	11.3	20.8

* Swinden and Johnson.[234]

These tests showed considerable superiority in properties over comparable carbon steel rails. Although the hardness was not much greater, the service life was increased by 148 to 500 per cent over that of carbon steel rails in similar locations. Good results were also obtained with angle bars of the same steel. No difficulty was encountered in rolling, hot sawing, cold straightening, drilling, or milling, and it was concluded that chromium steel rails were very well adapted to use at points of heavy traffic.

At the Inland Steel Company 2000 tons of 1 per cent chromium steel rails have been rolled. Nead reported* that alloy steel

* Private communication.

practice and controlled cooling are essential in the production to insure freedom from shatter cracks. He furnished the data in Tables 61 and 62 on the mechanical properties and wear resistance of such chromium rails.

TABLE 61.—MECHANICAL PROPERTIES OF ROLLED 90.20 SECTIONS OF CHROMIUM STEEL RAILS*

Steel No.	Composition, per cent						Rail	Tensile strength, lb./sq. in	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness
	C	Mn	Si	P	S	Cr						
1	0 53	1 00	0 208	0 014	0 024	0 67	*C*	132,980	80,740	16 3	38 3	266
2	0 54	0 75	0 174	0 014	0 025	1 07	*C*	133,380	79,770	16 3	39 3	275
3	0 63	0 85	0 228	0 020	0 030	1 02	*C*	145,150	96,650	8 8	14 7	297

* Nead, private communication

Waterhouse[441] described the properties of 3 per cent chromium steel rails now being tested in the United States. Basic open-hearth steel containing 0.25 per cent carbon, 0.69 per cent manganese, 0.25 per cent silicon, and 2.89 per cent chromium was rolled into 130-lb. rails. Tensile and impact tests in the rolled condition are given in Table 63.

TABLE 62.—COMPARATIVE WEAR, IN 44 MONTHS, OF 90.20 SECTIONS OF DIFFERENT RAIL STEELS*

Kind of steel	Composition, per cent						Wear, in sq in. of metal removed from original area of railhead		
	C	Mn	Si	P	S	Cr	Outside ratio	Inside ratio	Average
1 per cent chromium	0 63	0 85	0 228	0 020	0 030	1 02	0 210	0 197	0 203
Medium manganese	0 60	1 60	0.168	0 032	0 029		0 374	0 335	0 354
Carbon . .	0 76	0 76	0.188	0 033	0 031	.	0 405	0 253	0 328

* Nead, private communication

Drop tests, in spite of the high strength, were superior to average results on carbon steel rails. After 3 years of service on a curve during which 39 million tons of traffic went over the track, the

TABLE 63.—PROPERTIES OF BASIC OPEN-HEARTH RAILS CONTAINING 0.25 PER CENT CARBON AND 2.89 PER CENT CHROMIUM*

Location of specimen	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Izod impact, ft-lb.
Outside, head	179,350	112,800	14.5	35.7	12 0
Middle, head	178,250	111,350	13 0	26 1	10 4
Outside, base	179,000	109,750	15 0	33.1	15 5
Inside, base	178,800	106,700	15 0	32 1	17 0

* Waterhouse.(441)

wear was very slight, as shown in the following tabulation, in comparison with medium-manganese (1.5 per cent) rails at the same location:

Steel	Loss of metal in section, sq. in.	
	High rail	Low rail
3 per cent chromium steel	0.090	0 067
Medium-manganese steel	0 165	0 125

The analysis range recommended for this type of rail is 0.25 to 0.32 per cent carbon, 2.80 to 3.20 per cent chromium, 0.50 to 0.75 per cent manganese, and 0.25 to 0.40 per cent silicon.

H. AUTHORS' SUMMARY

1. The mechanical, chemical, electric, and other physical properties of the plain chromium steels might almost be predicted from the structures obtained with the various carbon and chromium contents discussed at length in a previous chapter. Naturally, some unpredictable variations in results occur owing to a lack of knowledge of solubility of chromium in ferrite, of the precise effect of the various types of carbide, and other factors. Nevertheless, the general physical properties of the plain low-chromium engineering steels are broadly in direct correlation with the structures.

2. Figures 100, 101, and 102 have been prepared as an illustrative summary of the data on the tensile properties and impact strength of low-chromium steels in the normalized condition, in the form of ¾ to 1-in. round bars, with silicon at a normal value of approximately 0.20 per cent. The increase in strength and the

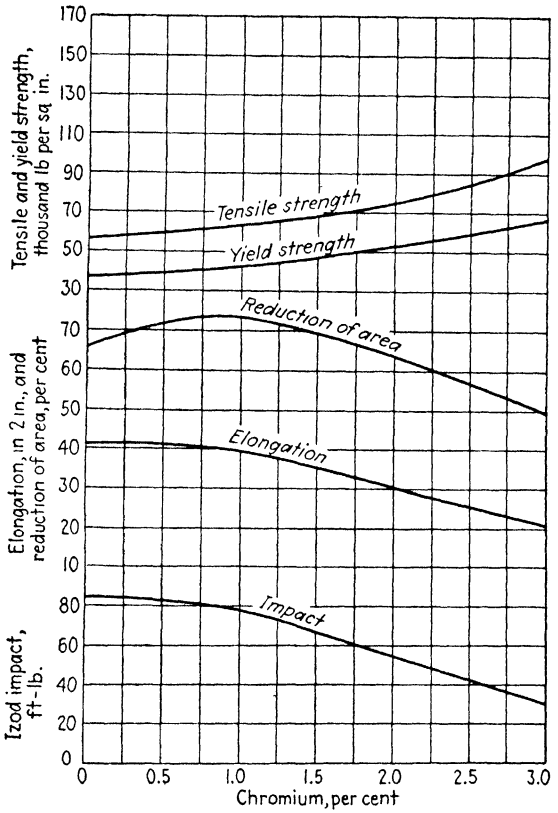


FIG. 100.—Effect of chromium on the mechanical properties of steel containing 0.10 per cent carbon and 0.30 to 0.60 per cent manganese. (*Union Carbide and Carbon Research Laboratories, Inc.*)

decrease in ductility with increasing chromium at a given carbon level occur as would be expected. The discontinuous behavior of the change in ductility with increasing chromium, as evidenced by proportionately higher ductility at the high chromium contents, is of particular importance. The properties of the steels change in a manner similar to the change in carbon steels up to some 2.5 per cent chromium. The nature of the steels with

increased chromium requires different heat treatment for development of the maximum mechanical properties.

3. With the heat-treated steel, the same phenomena take place, and the properties are modified in the same general manner. Figures 95 to 99 inclusive, given previously in this chapter,

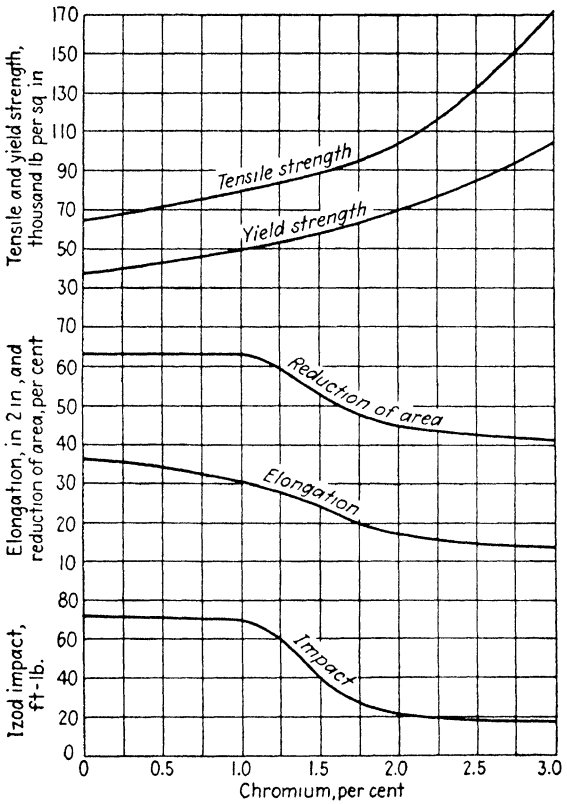


FIG. 101.—Effect of chromium on the mechanical properties of steel containing 0.20 per cent carbon and 0.30 to 0.60 per cent manganese. (*Union Carbide and Carbon Research Laboratories, Inc.*)

present an excellent illustration of the effect of 1 per cent chromium on the properties of steels with varying carbon content.

4. Perhaps the most important of all of the effects of chromium on the mechanical properties is the tendency to eliminate the mass effect. Even amounts as small as 0.5 per cent have an appreciable effect, and this quantity of chromium gives increased uniformity of hardening. One per cent of chromium produces

complete depth hardening in moderate sections with accompanying physical properties of high order, and this is further accentuated by increasing the chromium to 2 per cent. Three per cent of chromium changes this mass effect to such a degree that in

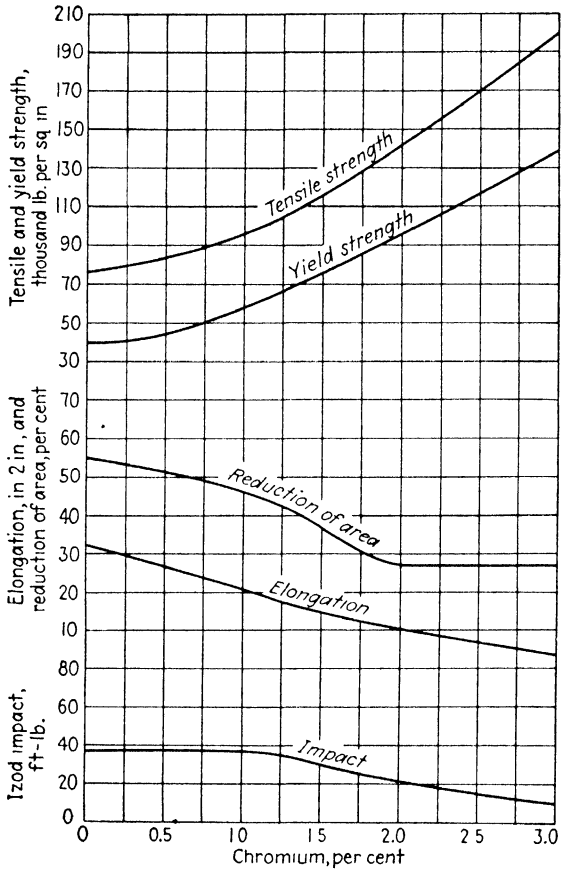


FIG. 102.—Effect of chromium on the mechanical properties of steel containing 0.30 per cent carbon and 0.30 to 0.60 per cent manganese. (*Union Carbide and Carbon Research Laboratories, Inc.*)

moderate sections uniform depth hardening is obtained in rolled and normalized specimens. The explanation for this effect of chromium may probably be found in the reduction of the critical rate necessary for hardening and in the slow rate at which the transformation progresses. In line with the structure and com-

position, the mass effect is greatly reduced in the chromium steels. Chromium thus provides a factor of safety, allowing the retention of desirable properties in larger sections.

5. Chromium up to 3.5 per cent has very little effect on the modulus of elasticity or on Poisson's ratio, thus permitting the use of standard formulas for chromium steels. Chromium, like many alloying elements, increases susceptibility to temper brittleness, but the degree is small. On the other hand, it increases appreciably the impact strength at temperatures below room temperature, particularly if it is present in combination with other alloys. The high-temperature strength [up to 400°C. (750°F.)] is markedly improved, this really being a resistance to tempering. At even higher temperatures, with small amounts of chromium the strengthening effect is still present but is of a lower order of magnitude, and the effect on creep strength at these higher temperatures is relatively small. The chromium, particularly in connection with high carbon, however, does contribute specific resistance to heat checking which makes it valuable for many purposes. The mechanical properties of the cast chromium steels compare well with those of the rolled and forged product, probably owing to the tendency of chromium to reduce dendritic segregation and improve soundness.

6. Chromium in the amounts considered in this chapter does not appreciably affect the density of steels, and in these amounts has little effect on the coefficient of expansion. While chromium reduces the thermal conductivity of steels, the effect of amounts less than 3 per cent is inappreciable. The thermal electromotive force of steels is increased by chromium even in amounts less than 3.5 per cent, and the electric resistance is likewise increased. From the more detailed work done in recent years it is evident that even small amounts of chromium decrease the rate of corrosion in the atmosphere, possibly by tending to build up a finer, more adherent corrosion product. The wear resistance of the steels in question is markedly improved, particularly as the chromium approaches 3 per cent with medium carbon, or 1 per cent with high carbon. The presence of chromium carbides, together with increased corrosion resistance, probably accounts for this phenomenon.

7. The proper use of chromium in quantities up to 3.5 per cent results in the production of steels of moderate cost with improved

properties of great variety. Broadly viewed, chromium increases the toughness of steels for a given strength in the lower carbon ranges, and increases the strength and hardness in the higher carbon materials, thus affording a medium with which to obtain balanced analysis and properties in plain chromium as well as in more complex alloy steels.

CHAPTER VIII

LOW-CHROMIUM ENGINEERING STEELS CONTAINING MANGANESE, SILICON, NICKEL, OR COPPER

Low-chromium Engineering Steels Containing Manganese—Low-chromium Engineering Steels Containing Manganese and Silicon—Low-chromium Engineering Steels Containing Nickel—Low-chromium Engineering Steels Containing Copper—Authors' Summary

Although the engineering and structural grades of plain low-chromium steels have wide application, by far the largest use of chromium in this type of steel is in combination with some other alloying element. Many of these are essentially chromium-type steels with a secondary element added for some specific reason. Others have characteristics determined primarily by another element so that the chromium assumes the secondary rôle.* The greater depth-hardening capacity conferred by chromium permits use of a larger section, simpler heat treatment, or reduction of the amount of a more expensive addition. Chromium also reduces dendritic segregation and heterogeneity so that it is often added to facilitate the manufacture of some of the more sensitive steels. In addition to increasing the uniformity of composition, structure, and hardness, chromium is added to take advantage of its effect on such specific properties as wear resistance and corrosion resistance. Another practical reason for the common use of chromium in many types of engineering steels is the low net cost of chromium steel. Chromium is one of the least expensive addition elements, and the efficiency of the addition is high, so that the use of chromium constitutes an economical means of obtaining the desired properties.

It should be emphasized here that most of the beneficial effects of chromium are obtained with combinations of chromium and other alloys. Chromium should not be regarded as unique among the alloying elements, nor is it to be inferred that chromium is in any sense a substitute for good steel-making practice.

* A complete discussion of the alloy steels in which chromium assumes a secondary rôle is, naturally, given in the other monographs of this series.

Chromium finds application in most of the low-alloy steels. It is used principally in conjunction with manganese, silicon, nickel, molybdenum, vanadium, copper, and tungsten. These steels cover practically all of the engineering and structural applications that do not require the special properties conferred by very high alloy contents.

A. LOW-CHROMIUM ENGINEERING STEELS CONTAINING MANGANESE

Manganese in excess of the amount required to avoid hot-shortness is added to practically all the medium-carbon 1 per cent chromium steels to increase their depth-hardening capacity. As was shown in Chapter VII, the S.A.E. specifications call for 0.50 to 0.80 per cent manganese, and more satisfactory properties are usually produced if the manganese is in the range of 0.70 to 0.90 per cent. This results in a somewhat more uniform response to heat treatment without material effect on the other characteristics of the steel. On the other hand, chromium in small amounts is also added to medium-manganese steel to reduce the section sensitivity and to increase homogeneity. A third class is the structural grade in which manganese and chromium are balanced so that each contributes to the production of a steel with many desirable properties. The combination also serves as a base for the addition of other alloys, such as silicon and copper, to produce high-strength structural steels.

94. Manufacture and Heat Treatment.—Chromium-manganese steel does not present any unique problems in melting or casting. In the pearlitic manganese steel with chromium up to 0.75 per cent the grain size is reduced so that more latitude in finishing temperatures in hot working can be tolerated without danger of shear cracking. Both manganese and chromium tend to reduce decarburization and oxide penetration so that surface defects, and therefore finishing costs, are lower. The rate of carburizing is increased by manganese and the tendency to distortion is reduced. Manganese has little effect on the critical temperatures on heating except for a slight lowering in the 1 to 1.5 per cent manganese grades with carbon above 0.2 per cent. As is well known, manganese decreases the critical cooling rate so that critical temperatures on cooling are lowered and the depth-hardening capacity is increased.

To obtain well-balanced compositions the ratios of chromium to manganese and the total amounts present must be carefully considered. Steels used in the rolled condition should have the carbon, manganese, and chromium so adjusted that the transformation of austenite is completed in the pearlitic range, *i.e.*, in the neighborhood of 600 to 700°C. (1110 to 1290°F.). In steels to be air cooled, containing up to 0.35 per cent carbon, the total of manganese plus chromium should not be greater than about 1.8 per cent with manganese above 1 per cent. As the chromium is increased above 1 per cent this relation must be modified somewhat. The manganese content of 2 per cent chromium steel is rather critical in steels which are used in the air-cooled condition and should not exceed about 0.50 per cent. In 3 per cent chromium steels the manganese content is not critical as the transformation on air cooling occurs in the intermediate temperature range of 300 to 400°C. (570 to 750°F.) with the production of pseudo martensite. In this grade the manganese may be as high as 1 per cent without harmful effect.

In medium-carbon heat-treated steels the total amounts of manganese plus chromium that give good properties are somewhat higher, about 2.0 to 2.2 per cent. In steels containing up to 1.0 per cent chromium, manganese improves uniformity, freedom from distortion, and depth of hardening and toughening, and enough may be added to give a total alloy content up to about 2.0 to 2.2 per cent, depending on carbon content. When the total alloy content exceeds this value there is an abrupt increase in tendency to distortion and cracking on quenching. In higher carbon grades such as are encountered in carburizing and tool steels, the maximum total alloy content for optimum results is somewhat lower, about 1.8 to 2.0 per cent chromium plus manganese.

95. Mechanical Properties of Chromium-manganese Structural Steels.—The mechanical properties of chromium steels with manganese up to 0.75 per cent and of manganese steels with chromium up to 0.75 per cent are improved in comparison with plain chromium or manganese steels to only a minor degree in small heat-treated specimens. The advantages of these steels lie in the less tangible factors such as moderate cost as compared with many of the low-alloy steels, less distortion, and decreased rejections.

TABLE 64.—MECHANICAL PROPERTIES OF 1-IN. ROUND BARS OF LOW-CHROMIUM STEELS CONTAINING MANGANESE*

Steel No.	Composition, per cent				As rolled or forged				Normalized at 900°C. (1650°F.)					
	C	Mn	Si	Cr	Tensile strength, lb /sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in , per cent	Reduction of area, per cent	Izod impact, ft-lb.	Brinell hardness
1	0.07	0 67	0 11	0 33	59 000	45,000	36 0	66 0	59,000	42,000	38 0	71.0	87	104
2	0 07	0 82	0.13	0 38	51,000	43.000	41 0	75 0	60,000	43.000	37 0	69 0	90	107
3	0 09	0 91	0 07	0 41	52.000	41,000	39 0	71 0	61,000	42,000	36 0	67 0	87	107
4	0 08	0 93	0 08	0 38	61,000	42,000	39 0	70 0	60,000	42,000	39 0	71 0	86	110
5	0 10	1.13	0 10	0 70	56,000	46,000	31 0	68 0	67,000	43,000	36 0	71 0	84	121
6	0 13	1 16	0 12	0 60	74.000	47,000	32 0	63 0	74,000	45,000	38 0	71 0	89	129
7	0 08	1 22	0 12	0 49	67,000	45,000	38 0	63 0	66,000	46,000	37 0	73 0	86	117
8	0 07	1 46	0 13	0 82	75,000	43.000	28 0	60 0	71,000	48,000	32 0	60 0	74	125
9	0 09	1 70	0 17	1 05	89,000	50,000	23 0	44 0	90,000	52,000	26 0	52 0	37	171
10	0 26	0 63	0 12	0 42	84,000	54,000	25 0	37 0	85,000	54,000	29 0	56 0	55	143
11	0 26	0 69	0 14	0 63	105.000	66,000	22 0	55 0	87,000	54,000	28 0	62 0	41	202
12	0 22	0 89	0 10	1 13	100,000	69,000	14 0	49 0	95,000	57,000	25 0	62 0	41	187
13	0 25	0 90	0 09	0 45	86,000	58,000	29 0	54 0	85,000	54,000	30 0	56 0	56	146
14	0 17	1 11	0 17	1 37	95,000	59,000	24 0	47 0	96,000	58,000	24 0	56 0	35	170
15	0 31	0 78	0 21	1 03	105,000	66,000	22 0	55 0	109,000	66,000	23 0	59 0	36	202
16	0 37	1 17	0 21	1 04	127,000	116,000	1 0	2 0	148,000	107,000	5 0	8 0	34	146
17	0 44	1 35	0 34	1 12		.		. .	162,000	92,000	3 0	4 0		
18	0 50	1 37	0 22	0 31	123,000	80,000	11.0	.	127,000	75,000	15 0	27 0	7	241
19	0 44	1 73	0 14	0 64		.	.	..	141,000	114,000	3 0	3 0	4	293
20	0 43	1 75	0 34	0 40	123.000	82,000	13 0	35 0	138,000	94,000	12 0	25 0		

* Kinzel and Miller.(238)

In rolled and normalized steels the combination of chromium and manganese was found by Kinzel and Miller[288] to produce

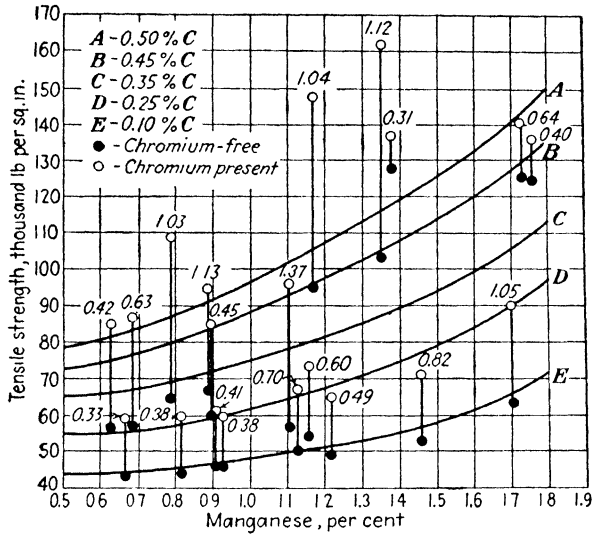


FIG. 103.—Improvement in tensile strength of normalized manganese steels by chromium addition. (*Kinzel and Miller.*[288])

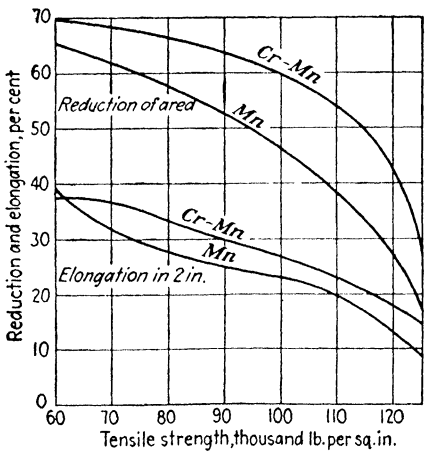


FIG. 104.—Elongation and reduction of area of manganese and chromium-manganese steels of the same carbon content as a function of tensile strength. See Tables 64 and 65 for composition. (*Kinzel and Miller.*[288])

properties fitting the steel for structural applications. As shown in Table 64 and Fig. 103, chromium in small amounts increased

the strength of manganese steel. The increase became extremely marked as the carbon content increased to 0.45 per cent. In all ranges, the chromium-manganese steels had higher ductility than the plain manganese steels as shown in Table 65 and Fig. 104.

TABLE 65.—EFFECT OF CHROMIUM ON THE DUCTILITY OF MANGANESE STEELS*

Steel	Composition, per cent		Approximate tensile strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent
	C	Mn			
1, 2, 3, 4	†	†	60,000	38	69
Plain Mn steel	0 08	1 6	60,000	39	65
5, 6, 7	†	†	70,000	37	72
Plain Mn steel	0 10	1 8	70,000	32	62
10, 11, 12, 13, 14	†	†	90,000	29	60
Plain Mn steel	0 25	1 7	90,000	25	52
15	†	†	110,000	23	59
Plain Mn steel	0 35	1 75	110,000	20	39
18	†	†	125,000	15	27
Plain Mn steel	0 45	1 6	125,000	8	15

* Kinzel and Miller.(288)
† See Table 64

The excellent properties of these steels in the 90,000 lb. per sq. in. tensile-strength range led to the production of a welded test tank, 24 in. in diameter by 7 ft. 9 in. long, with a wall thickness of $\frac{3}{8}$ in. and with the following analysis: 0.28 per cent carbon, 0.90 per cent manganese, 0.33 per cent silicon, and 0.31 per cent chromium. After oxyacetylene welding with a carbon-steel rod, the tank was annealed at 900°C. (1650°F.) for 1 hr. It was then tested to destruction and failed at a hydrostatic pressure of 2450 lb. per sq. in. or 78,500 lb. per sq. in. fiber stress. The circumference expanded $3\frac{3}{4}$ in. before rupture. Tensile specimens taken from the tank after failure gave the following properties:

Direction	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent
Longitudinal	91,550	65,850	27
Transverse	95,150	76,400	27
Transverse with welded seam	97,600	77,500	25 (in bending)

It is apparent that substitution of chromium for part of the manganese effects a substantial improvement over the more widely used plain manganese structural steel. In the discussion of Kinzel and Miller's paper it was brought out that the reasons for this probably lie in the reduced tendency to ingot segregation as well as in improved hardening action and grain refinement.

96. Mechanical Properties of Chromium-manganese Spring Steels.—One of the most effective applications of chromium-manganese steels is in heat-treated springs. Both alloys reduce

TABLE 66.—COMPOSITIONS AND QUENCHING TEMPERATURES OF STEELS USED BY HOUDREMONT AND BENNEK[365]

Kind of steel	Composition, per cent					Quenching temperature		Quenching medium
	C	Mn	Si	Cr	V	°C.	°F.	
Carbon	0.90	0.39	0.25			840	1545	Oil
Silicon (1.5 per cent)	0.44	0.60	1.49			830	1525	Water
Silicon (2.7 per cent)	0.75	0.34	2.70			840	1545	Water
Manganese	0.61	1.81	0.39			840	1545	Water
Silicon-manganese	0.46	0.92	0.95			840	1545	Water
Chromium-vanadium	0.47	0.46	0.23	1.06	0.16	900	1650	Oil
Chromium-manganese	0.43	0.84	0.17	0.97		850	1560	Oil

the decarburization in rolling, forming, and heat treating; as pointed out by Hankins and Becker,[324] this is the primary factor determining the fatigue limit of springs that are not ground after heat treatment. The properties of 1 per cent chromium steels with relatively high manganese have been studied by Houdremont and Bennek,[365] who found that complete hardening required the presence of a fairly high manganese content. These investigators

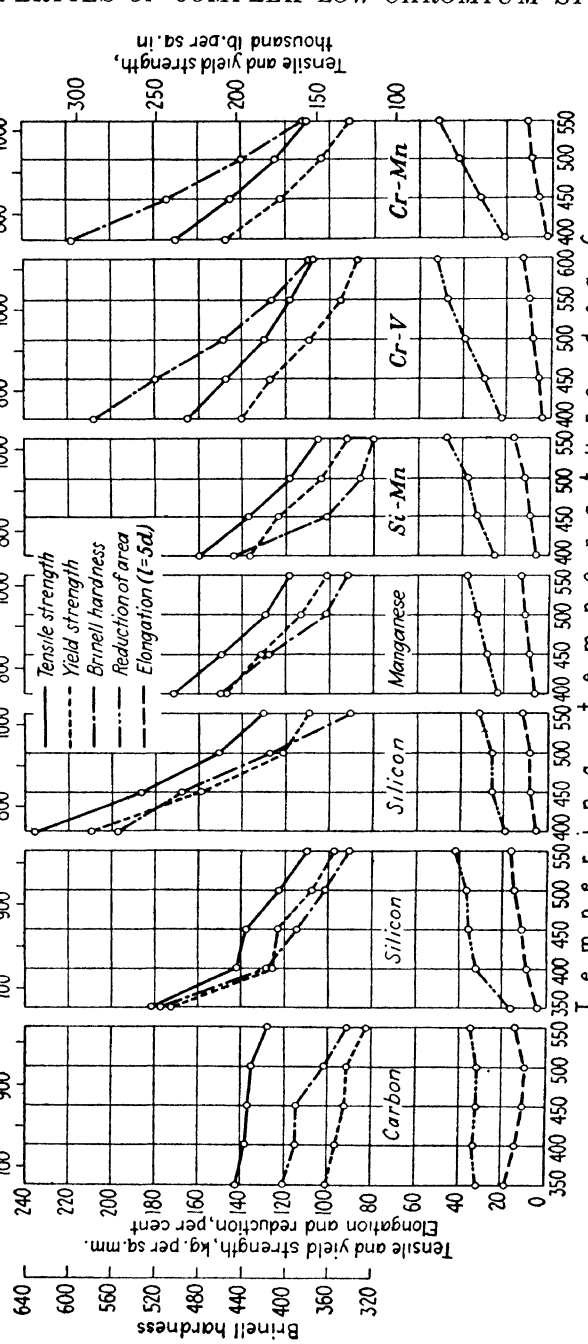


FIG. 105.—Effect of tempering on the mechanical properties of spring steels. Compositions are given in Table 66. (*Houdremont and Bennek.*(565))

determined the mechanical properties after tempering of 7 spring steels, compositions and quenching temperatures of which are given in Table 66. The mechanical properties are shown in Fig. 105.

Malcolm[143] made short-time elevated-temperature tests on a medium-carbon chromium-manganese steel with the results given in Table 67.

TABLE 67.—ELEVATED-TEMPERATURE PROPERTIES OF A 0.55 PER CENT CARBON, 1.25 PER CENT MANGANESE, 0.45 PER CENT CHROMIUM STEEL AFTER OIL QUENCHING FROM 785°C. (1450°F.) AND TEMPERING AT 650°C. (1200°F.)*

Temperature of test		Tensile strength, lb /sq. in.	Johnson's elastic limit, lb./sq. in.	Elongation in 2 in , per cent	Reduction of area, per cent
°C.	°F.				
21	70	145,000	110,000	20 0	49.0
205	400	131,150	99,000	16 3	48.3
315	600	129,830	91,750	15 8	40.3
425	800	131,750	82,830	21 8	55.1
540	1000	89,000	56,000	22 6	67.6

* Malcolm.[143]

97. Mechanical Properties of Chromium-manganese Steels Containing 2 Per Cent Chromium.—On account of the strong air-hardening tendencies of 2 per cent chromium steel, there is little advantage to be gained from manganese above 0.6 per cent. In small and medium sections the austenite transformation is split, part of the section transforms to pearlite and part to pseudo martensite. This results in non-uniform hardening with slight non-uniformity of section and relatively low ductility and impact strength. In heat-treated material penetration of hardening in smaller sections is obtained with chromium well below 2 per cent so that there is no advantage in manganese over 0.6 per cent. The properties of such steels have been determined by Genders, Davidson, and Marks, and reported by Greaves.[449] The analyses of the steels are shown in the table at the top of page 239. They were forged to $\frac{3}{4} \times 1\frac{3}{4}$-in. bars and treated in that section. On slow heating and cooling, manganese lowered the critical temperatures slightly. Mechanical properties in the

Steel No.	Composition, per cent			
	C	Mn	Si	Cr
1	0 39	0 33	0.26	1 97
2	0 39	0 50	0.24	1.96
3	0.39	0 72	0 23	1.98
4	0.31	0 90	0 25	1.94

TABLE 68.—MECHANICAL PROPERTIES OF FORGED, ANNEALED, AND NORMALIZED CHROMIUM-MANGANESE STEELS*

Steel No.	Treatment: Heated to °C	Treatment: Heated to °F.	Treatment: Cooled in	Tensile strength, lb./sq in	Yield strength, lb./sq in	Elongation in 2 in , per cent	Reduction of area, per cent	Average Izod impact value, ft-lb.	Brinell hardness
1	As forged			118,600	69,000	24 0	61 0	26 0	231
2	As forged			125,500	75,600	20 0	62 0	15 0	259
3	As forged			178,000	113,800	14 0	34 0	8 0	356
4	As forged			175,200	112,000	12 0	31 0	10 0	354
1	900	1650	†	101,100	45,900	27 0	47 0	15 0	199
2	900	1650	†	104,200	47,900	25 0	46 0	9 0	207
3	900	1650	†	106,400	51,500	23 0	48 0	7 0	214
4	900	1650	†	100,200	49,000	25 0	54 0	9 0	199
1	900	1650	Air	110,900	62,700	23 0	54 0	24 0	216
2	900	1650	Air	128,700	82,000	16 0	59 0	9 0	281
3	900	1650	Air	171,000	105,300	15 0	34 0	6 0	344
4	900	1650	Air	167,000	103,700	16 0	36 0	8 0	330
1	1000	1830	Air	123,900	74,600	19 0	54 0	15 0	254
2	1000	1830	Air	161,900	107,500	13 0	34 0	6 0	335
3	1000	1830	Air	166,200	109,800	14 0	35 0	5 0	345
4	1000	1830	Air	162,000	103,100	16 0	37 0	6 0	317
1	1100	2010	Air	140,600	102,300	10 0	36 0	7 0	303
2	1100	2010	Air	157,700	104,900	15 0	59 0	5 0	327
3	1100	2010	Air	164,100	105,300	14 0	32 0	5 0	332
4	1100	2010	Air	159,800	99,900	15 0	31 0	6 0	324
3	900	1650	Air‡	164,000	123,200	14 0	42 0	. . .	333
3	1000	1830	Air‡	162,000	127,800	14 0	42 0	.	327
3	1100	2010	Air‡	159,600	121,000	15 0	45 0	. . .	327

* Genders, Davidson, and Marks, according to Greaves.[449]

† Cooled at a rate of 0 3°C. (0 5°F.) per min.

‡ Followed by tempering at 375°C. (705°F.).

forged, annealed, and normalized conditions are shown in Table 68. Manganese greatly increased the tensile strength and lowered the ductility and impact strength of forged and of normalized specimens. Some improvement of the high-manganese steel was produced by tempering. The high order of properties in steel 1 containing 0.33 per cent manganese, however, is worthy of note.

TABLE 69.—MECHANICAL PROPERTIES OF CHROMIUM-MANGANESE STEELS OIL QUENCHED FROM 820°C. (1510°F.) AND TEMPERED AS SHOWN*

Steel No.	Tempering temperature			Tensile strength, lb./sq. in.	Yield strength, lb./sq. in	Elongation in 2 in., per cent	Reduction of area, per cent	Average Izod impact value, ft-lb.	Brinell hardness
	°C.	°F.	Cooled in†						
1	550	1020	.	155,200	139,600	18 0	55 0	15 0	329
2	550	1020	..	162,100	147,900	17 0	51 0	9 0	342
3	550	1020	..	156,900	142,900	16 0	51 0	5 0	330
4	550	1020	..	156,200	142,900	18 0	54 0	3 0	328
1	600	1110	..	144,900	126,700	19 0	56 0	20 0	310
2	600	1110	..	146,000	127,200	19.0	55 0	16 0	307
3	600	1110	..	149,000	130,800	19 0	55 0	8 0	312
4	600	1110		137,400	120,200	22 0	60 0	10 0	290
1	650	1200	.	124,300	103,200	23 0	62 0	54 0	259
2	650	1200	.	128,700	106,900	23 0	62 0	42 0	269
3	650	1200		130,800	110,300	23 0	64 0	32 0	269
4	650	1200	.	122,800	102,200	25 0	66 0	26 0	254
1	650	1200	W	121,200	96,800	22 0	64 0	55 0	257
	650	1200	F	116,500	91,900	22 0	64 0	18 0	243
2	650	1200	W	126,000	102,700	23 0	63 0	60 0	268
	650	1200	F	121,900	99,900	23 0	62 0	13 0	256
3	650	1200	W	126,300	103,900	23 0	66 0	65 0	266
	650	1200	F	122,800	101,800	25 0	61 0	10 0	260
4	650	1200	W	123,000	101,300	24 0	66 0	70 0	258
	650	1200	F	129,200	99,000	26 0	64 0	3 0	251

* Genders, Davidson, and Marks, according to Greaves [449]

† W, water quenched from tempering temperature, F, furnace cooled at 0.3°C. (0.5°F.) per min.

After annealing, the effect of manganese was not noticeable except for a drop in impact strength. Oil hardening and tempering developed good tensile properties in all the steels, as shown in Table 69. Air cooling from the tempering temperature resulted

in fairly low impact strength in the higher manganese steels and, as shown in Table 70, the susceptibility to temper brittleness was increased by manganese.

It may be concluded from the work by Genders, Davidson, and Marks that, in the rolled or normalized condition, 2 per cent chromium steel with a manganese content below 0.5 per cent has properties that justify careful consideration. It has high strength and ductility and adequate shock resistance which can be realized in a low-cost alloy steel with either a simple heat treatment or none at all. The higher manganese steels have properties that should make them suitable for use in large sections provided the rate of cooling after tempering is sufficiently rapid to suppress temper brittleness.

As mentioned before, manganese is not critical in 3 per cent chromium steel. In small sections it has little significant effect, but it increases the uniformity of hardening in large sections. For this reason 3 per cent chromium steels are usually made with 0.50 to 0.75 per cent manganese so that a given heat will not be restricted in its applicability.

98. Fabrication and Uses.—Manganese has little influence on the properties affecting the shearing, forming, and machining of the steels that are essentially of the chromium type, *i.e.*, containing more than 0.50 per cent chromium. In the manganese type, containing more than 1.35 per cent manganese, however, the addition of chromium facilitates the fabrication by improving the characteristics of the steel in the air-cooled condition. While the grain size is refined by chromium to the point where shearing is improved, the grain is not sufficiently small to affect machinability adversely. The increased uniformity in hardness facilitates all cutting and forming operations. Welding by arc or oxyacetylene processes may be carried out without difficulty in obtaining complete fusion or in avoiding air hardening on low-carbon chromium-manganese steel, but with high-strength grades (90,000 lb. per sq. in.) welding should be followed by a stress-relieving anneal or normalizing treatment.

The low-chromium manganese steels are an improved grade of pearlitic manganese steel and are suitable for heat-treated machine parts such as steering parts, front axles, connecting rods, etc. While the greatest application for these steels in the rolled or normalized condition is in structural steel with 70,000 to

TABLE 70.—TEMPER BRITTLENESS OF CHROMIUM-MANGANESE STEELS*

Steel No.	Izod impact value, ft-lb.													
	Oil quenched from 825°C. (1515°F.), tempered 2 hr at 630°C. (1165°F.), and cooled		After reheating temper-brittle (slowly cooled) material to temperatures shown and cooling quickly (in water) or slowly (at 0.3°C per min.) from											
			625°C (1155°F.)		600°C (1110°F.)		575°C. (1065°F.)		550°C (1020°F.)		500°C (930°F.)		450°C. (840°F.)	
	Quickly	Slowly	Quickly	Slowly	Quickly	Slowly	Quickly	Slowly	Quickly	Slowly	Quickly	Slowly	Quickly	Slowly
1	55.3	18.0	65	27	60	23	60	22	30	21	23	20	22	21
2	60.0	13.5	66	16	57	14	50	17	30	18	21	21	19	18
3	64.7	9.8	66	18	59	9	41	13	22	13	11	14	14	10
4	70.2	3.3	80	6	55	2	24	4	6	8	7	6	5	2

* Genders, Davidson, and Marks, according to Greaves.[449]

90,000 lb. per sq. in. tensile strength, the practice of using simple heat treatments for machine parts is becoming more common, and these steels are particularly well fitted for normalizing. On account of the reduced tendency to decarburization, steels based on chromium and manganese are particularly well suited for use in springs.

B. LOW-CHROMIUM ENGINEERING STEELS CONTAINING MANGANESE AND SILICON

Chromium-manganese-silicon steels have long been known, but their full possibilities have only been realized in recent years. In the early days of the automobile these steels were used for springs and gears and to some extent for axles and shafts. As requirements became more exacting they were discarded in favor of more expensive grades that were less sensitive to variation in analysis and heat treatment. However, with the development of more closely controlled melting practice and heat-treating furnaces, this type of steel is returning to more common use and may be expected to find wider application in springs and forgings. It has also found application as a high-strength structural steel in recent years.

It might be considered logical to discuss first chromium-silicon steels with less than 0.5 per cent manganese, but these steels have practically no industrial application, higher manganese having been used ever since they were industrially applied. Although the manganese content in a large number of such steels is no higher than in other similar steels, they are known to the trade as the chromium-manganese-silicon type.

Steel of this type has been used for machine and structural parts and even as a tool material. The compositions range up to 3 per cent chromium, 2 per cent manganese, and, although special steels discussed elsewhere contain up to 2 per cent silicon, the silicon content of the engineering grade is usually limited to 1 per cent. This has resulted from the fact that silicon up to 1 per cent reduces decarburization, oxide penetration, and burning in normal industrial furnace atmospheres, but between 1 and 2 per cent silicon a tendency to burning develops which produces a poor surface condition. This fact has been quantitatively checked by Crafts* at the Union Carbide and Carbon Research

* Unpublished investigation.

Laboratories, Inc. Steels with higher amounts of silicon appear to be free from this defect, as 2 per cent silicon spring steel and 4.5 per cent silicon transformer steel are rolled without difficulty. The reduced decarburization and higher endurance limit conferred by silicon make it a desirable addition to spring steel, and the increased strength without depression of the austenite transformation temperature makes it an equally desirable component of high-strength structural steel and normalized machine parts. Steels containing silicon above the normal 0.25 per cent require higher quenching temperatures which do not minimize distortion, so that, in view of the recent demand for noiseless gears, it is doubtful whether silicon can be effectively utilized in steels for this application.

99. Manufacture and Heat Treatment.—In the manufacture of chromium-manganese-silicon steel the manner and degree of deoxidation are of primary importance in determining the quality of the product and its suitability for service. With good practice this type of steel is reasonably free from banding and nonmetallic inclusions, and this condition should be produced in steels for the majority of uses. However, if initial deoxidation is not thorough, the steel may contain a large amount of elongated inclusions. While undesirable for most purposes, these inclusions are often considered desirable for spring steel. In fact, intentional additions of slag are occasionally made to bring about a fibrous structure that has a high resistance to impact where the stress is transverse to the direction of rolling.

As mentioned before, silicon in amounts up to 1 per cent reduces the tendency to burning so that ingots may be soaked at a higher temperature. The number of surface defects is reduced so that, in addition to reduction of cost, the quality of structural and spring steels is improved. Silicon has a refining influence on grain size that permits a greater range of finishing temperatures without much variation in strength or ductility. This facilitates making structural steel to a close specification, reduces wear on shearing dies, and practically eliminates shear cracking.

As might be anticipated, the addition of silicon to chromium-manganese steel has a simple additive effect on the critical temperatures on heating. Although published data are lacking, this has been confirmed many times in unpublished work of the Union Carbide and Carbon Research Laboratories, Inc. As in steel

low in manganese and chromium, the addition of 1 per cent silicon raises Ac_1 by about 20°C. (35°F.) and Ac_3 by about 25°C. (45°F.). The higher quenching temperature required for higher silicon steel imposes a limitation on its use in applications where accuracy of dimension and freedom from distortion overbalance such beneficial effects as higher fatigue limit and better rolled surface.

Silicon has a mild influence on the transformation of austenite on cooling, that tends to increase the critical cooling rate required for hardening. In quenching, the increase is so small as to be practically inappreciable, but in air-cooled low- and medium-carbon steels the presence of 0.8 per cent silicon instead of about 0.25 per cent permits the total manganese plus chromium content, as discussed in the preceding section, to be raised by 0.10 per cent without unbalancing the hardening characteristics. This greatly increases the heating and cooling range, resulting in a pearlitic structure. In structural steel this is of the utmost importance as silicon not only raises the strength itself, permits larger amounts of chromium and manganese to be used with safety, but also reduces the necessity for normalizing after rolling.

Although the addition of up to 1.0 per cent silicon has been found to reduce decarburization markedly at the high temperatures used for rolling, it has relatively less effect at the lower temperatures used for heat treatment. Manganese and chromium, however, have a strong effect in all temperature ranges, and silicon contributes to this so that chromium-manganese-silicon steel has been found to have relatively little decarburization in the initial rolled surface and to be relatively free from decarburization in heat treatment. As silicon retards carburization to about the same extent as chromium and manganese accelerate it, the combined effect in the common low-alloy grades is to give a carburizing rate about equal to or slightly higher than that of plain carbon steel.

100. Mechanical Properties of Low-chromium Steel Containing Manganese and Silicon.—Published reports of systematic investigations of chromium-manganese-silicon steels cover only certain limited ranges so that the mechanical properties of the series are discussed by individual investigations and without any attempt at correlation. The chromium-manganese-silicon steels developed by Kinzel and used principally for structural purposes constitute one range. Another range is represented by the

TABLE 71.—MECHANICAL PROPERTIES OF CHROMIUM-MANGANESE-SILICON (CROMANSIL) STEEL

Series*	Composition, per cent				Quenching			Tempering temperature		Tensile strength, lb /sq in.	Yield strength, lb./sq in	Elongation in 2 in., per cent	Reduction of area, per cent	Izod impact, ft-lb.	Brinell hardness
					Temperature		Medium								
	C	Mn	Si	Cr	°C	°F		°C	°F						
A1	0 34	1 04	0 91	0 38	900	1650	Air			111 000	72,000	25	60	26	207
				0 73	900	1650	Air			122,000	75,000	20	58	12	241
				0 95	900	1650	Air			126,000	79,000	21	59	13	302
A2	0 34	1 04	0 91	0 38	900	1650	Oil	425	800	159,000	140,000		.	23	340
				0 73	900	1650	Oil	425	800	201,000	177,000	10	42	26	375
				0 95	900	1650	Oil	425	800	201 000	178,000	10	38	22	387
A3	0 34	1 04	0 91	0 38	900	1650	Oil	500	930	151 000	136,000	18	50	35	321
				0 73	900	1650	Oil	500	930	166,000	150 000	15	50	24	340
				0 95	900	1650	Oil	500	930	167 000	151 000	15	48	24	340
B	0.31	1 13	0 87	0 24	As rolled		.			111 600	60,100	25 4	42 1		217
					900	1650	Air			109 400	76 200	29 6	54.1	45 5	215
					900	1650	Water	480	900	153,300	131,700	17 7	35 8	...	302
					900	1650	Water	540	1000	143,700	131,400	19 3	40 0	42 0	297
					900	1650	Water	595	1100	128 200	113,500	22 2	44 9	48 7	269
					900	1650	Water	650	1200	113 800	101,700	25 8	47 8	66 0	248

* Results for series *A* by Kinzel;[221] for series *B* by Bremmer [265]

chromium-silicon-manganese gear and spring steels formerly used in automotive construction. The investigation of Genders, Davidson, and Marks on the effect of manganese and silicon in 2 per cent chromium steel is also included in this discussion.

Kinzel,[221] after a study of silicon-manganese steel, concluded that the best composition contained about 1 per cent of each alloying element. The steel was lacking in depth-hardening capacity, and tests were made to determine the effect of chromium. A heat containing 0.34 per cent carbon, 1.04 per cent manganese, and 0.91 per cent silicon was split into three ladles to which chromium was added to give 0.38, 0.73, and 0.95 per cent respectively. Tensile- and impact-test data are given (series *A*) in Table 71. It will be noted that in the fully heat-treated condition the properties were excellent irrespective of the chromium content and were considered to be equivalent to those of other high-quality low-alloy steels. In the normalized condition, however, it is evident that the safe limit of chromium content in this steel is between 0.38 and 0.73 per cent if sacrifice of the impact strength is to be avoided. Kinzel's study resulted in the development of a

TABLE 72.—COMPOSITION AND PROPERTIES OF CHROMIUM-MANGANESE-SILICON (CROMANSIL) STEEL*

Application	Composition, per cent				Tensile strength, lb./sq. in	Yield strength, lb./sq. in	Elongation in 8 in., per cent	Reduction of area, per cent	Izod impact, ft-lb.	Brinell hardness
	C	Mn	Si	Cr						
Staybolts	0.05	1.12	0.87	0.25	71,000	54,000	31	75	64	
Boiler plate (1 in.), longitudinal	0.21	1.17	0.72	0.47	99,000	51,000	16			210
Same, transverse					98,000	51,000	14		25	
Structural	0.31	1.10	0.60	0.44	108,000	68,000	25†	63	42	220

* Tull.[376]
† In 2 in.

low-chromium steel containing about 1.25 per cent manganese and 0.50 to 1.00 per cent silicon, known commonly in this country as "Cromansil" (a coined word from chromium, manganese, and silicon).

Typical compositions and mechanical properties of this steel for various applications were reported by Tull[376] as given in Table 72. He stated that the steel was relatively free from segregation, had a small grain size, and could be readily rolled, pierced, and drawn.

The properties of similar steel in the form of 6⅝ in. outside diameter (0.352 in. wall) tubing were determined by Bremmer[265] and are given in Table 71 (series *B*). The ductility and impact strength of this tubing were superior to those of silicon-manganese, manganese, manganese-molybdenum, and chromium-molybdenum steels of similar strength, and resulted in the use of a large tonnage in deep oil-well casings.

The effect of mass on Cromansil steel was reported by Miller[431] for plate from ½ to 2 in. thick in the rolled condition. The steel contained 0.21 per cent carbon, 1.17 per cent manganese, 0.72 per

TABLE 73.—EFFECT OF MASS ON CHROMIUM-MANGANESE-SILICON (CROMANSIL) STEEL*

Section	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 8 in., per cent	Reduction of area, per cent	Izod impact, ft-lb.
0.5-in. plate:					
Longitudinal	92,000	50,000	20 0	56	35
Transverse	91,000	51,000	18 0	54	
1-in. plate:					
Longitudinal	99,000	51,000	16 0		
Transverse	98,000	51,000	14 0		25
1.5-in. plate:					
Longitudinal	89,000	56,000	19.0		
Transverse	89,000	53,000	17.0		24
2-in. plate:					
Longitudinal	86,000	53,000	20 0		
Transverse	88,000	54,000	15 0		20

* Miller.[431]

cent silicon, and 0.47 per cent chromium and had the mechanical properties shown in Table 73. The 2-in. thick plate was slightly lower in all properties, but the difference was negligible for structural purposes.

The low-temperature impact strength in the normalized condition of a Cromansil steel containing 0.09 per cent carbon, 1.47 per cent manganese, 0.55 per cent silicon, and 0.48 per cent chromium was found by Egan, Crafts, and Kinzel[385] to be as follows:

Temperature		Izod impact value, ft-lb
°C.	°F.	
Room	Room	48
−50	−60	11
−80	−110	10
−115	−175	5 5
−150	−240	2 5
−185	−300	3 5

Norwood[432] reported tests of a Cromansil steel containing 0.06 per cent carbon as follows:

Temperature		Charpy impact value, ft-lb.
°C	°F.	
20	70	59
−18	0	51
−40	−40	41
−50	−60	37

It is apparent from Norwood's values that high impact resistance is retained at temperatures encountered under atmospheric conditions. Norwood also gave the creep strength of 0.20 per cent and 0.26 per cent carbon Cromansil steels as 5750 and 6570 lb. per sq. in. respectively for a creep rate of 1 per cent in 10,000 hr. at 540°C. (1000°F.). These values were found to be about equal to 3.5 per cent nickel, low nickel-chrome, and chrome-vanadium steels of similar room-temperature strength. The thermal conductivity was found to be about one-quarter of that of Armco iron and 40 per cent of that of 0.15 per cent carbon firebox

quality steel of 55,000 lb. per sq. in. tensile strength. The higher fatigue limit of silicon steel found by Jones[248] was confirmed by Norwood, who found a ratio of endurance to tensile strength of 55 per cent for the 0.75 per cent silicon Cromansil steel. Staybolt steel had a fatigue limit of 38,500 lb. per sq. in. as reported by Tull.[376]

101. Fabrication and Uses of Low-chromium Steel Containing Manganese and Silicon.—Fabrication of Cromansil steel, containing approximately 0.90 to 1.50 per cent manganese, 0.60 to 0.90 per cent silicon, and 0.30 to 0.60 per cent chromium with carbon adjusted to give the desired strength, is carried out by normal methods and usual equipment in grades having a tensile strength up to 90,000 lb. per sq. in. It may be sheared, punched, scarfed, and formed with no more difficulty than would normally be anticipated in high-strength steel. Tests on riveted joints were made at Lehigh University and by A. E. Gibson of the Wellman Engineering Company and reported by Norwood.[432] Rivets of Cromansil made tight joints and developed high strength but were not too hard to chip when the carbon content did not exceed 0.20 per cent. Butt joints failed in tension in the outer row of rivets at a stress in the net section of 106,000 lb. per sq. in. Lap joints failed by shearing of the rivets at a single shear stress of 67,000 for air-hammered rivets and 78,000 lb. per sq. in. for hydraulically driven rivets. Rivets of 0.20 per cent carbon Cromansil had a Rockwell *B* hardness of 84 and double shear strength of 64,000 lb. per sq. in. before driving. After driving, the hardness had increased slightly to 90 and the double shear strength was 112,000 lb. per sq. in.

Lyse and Godfrey[394] made shearing tests on steel containing 0.20 per cent carbon, 1.19 per cent manganese, 0.67 per cent silicon, and 0.45 per cent chromium in the rolled condition with the following results:

Test	Tensile strength, lb./sq. in	Yield point, lb./sq. in.	Elongation, per cent	Modulus, million lb./sq. in.
Tensile	85,600	54,300	30.5	30 43
Torsion (shear)	84,200	31,100	.	11 88

From these data Poisson's ratio was found to be 0.276, a value which seems to be too low, and the ratio of yield point in shear to yield point in tension was 0.573.

Welding may be performed by either arc or oxyacetylene processes. Detailed procedures were given by Westin.[442] To utilize fully the high strength a suitable filler rod should be used to raise the strength of the weld metal. The Cromansil analysis itself has been found to give good results as a filler rod. In grades having a carbon content of 0.10 to 0.15 per cent with a tensile strength of 75,000 to 80,000 lb. per sq. in., the ductility is such that heat treating is not necessary. Higher strength grades should be annealed.

As indicated before, the 0.5 per cent chromium, 1.0 per cent manganese, 0.8 per cent silicon steel has been used principally for structural purposes in bar, sheet, plate, and tubing in applications requiring high-strength structural steel. It has been used in railroad rolling stock, cranes, ship, bridge, and general machinery construction. The principal advantages of this type of high-strength steel lie in the high order of uniformity and ductility and the low cost of alloys and manufacture.

102. Properties of Cromansil Castings.—The Cromansil analysis has also been used in castings. Grotts[361] recommended this composition for abrasion resistance and where high strength and ductility are required. The impact strength is sufficient for many purposes and can be raised by small additions of vana-

TABLE 74.—MECHANICAL PROPERTIES OF CROMANSIL CASTINGS*

Composition, per cent					Quenching			Tempering temperature		Tensile strength, lb/sq. in.	Yield strength, lb/sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent
					Temperature		Medium						
C	Mn	Si	Cr	V	°C.	°F		°C.	°F.				
0.37	1.49	0.46	0.52		900	1650	Air	675	1250	117,000	73,000	20	48
0.39	1.38	0.57	0.63	...	845	1550	Air	370	700	124,000	75,000	21	49
0.42	1.45	0.80	0.38	0.16	900	1650	Oil	620	1150	116,000	74,000	21	41
0.42	1.45	0.80	0.38	0.16	900	1650	Air	620	1150	116,000	74,000	19	43
0.42	1.45	0.80	0.38	0.16	900	1650	Oil	790	1450	105,000	73,000	26	49
0.42	1.45	0.80	0.38	0.16	900	1650	Air	790	1450	108,000	62,000	20	47

* Critchett.[384]

dium which produces more uniformly finer grain in the cast materials. Data on Cromansil steel castings as given by Critchett[384] are reproduced in Table 74.

103. Mechanical Properties of 1 Per Cent Chromium Steel Containing Manganese and Silicon.—As discussed by Greiner, Marsh, and Stoughton,[389] steels containing 0.75 per cent manganese, 0.50 per cent silicon, and 0.75 per cent chromium came into general use after 1900 for automotive parts such as springs, axles, and shafts. The tensile properties shown in Table 75 were taken from a catalogue published in 1912 by the Halcomb Steel Com-

TABLE 75.—MECHANICAL PROPERTIES OF CHROMIUM-MANGANESE-SILICON STEEL CONTAINING 0.6 PER CENT CHROMIUM, 0.8 PER CENT MANGANESE, AND 1.20 PER CENT SILICON, OIL QUENCHED FROM 845°C. (1550°F.) AND TEMPERED AS SHOWN*

Carbon, per cent	Tempered at		Tensile strength, lb./sq. in	Yield strength, lb./sq in.	Elongation in 2 in , per cent	Reduction of area, per cent	Brinell hardness
	°C.	°F.					
0.15	315	600	115,000	75,000	21	67	207
0.30	425	800	184,000	160,000	14	51	375
0 30	540	1000	145,000	128,000	20	60	300
0 30	650	1200	112,000	100,000	25	68	219
0 45	425	800	224,000	199,000	13	46	434
0 45	540	1000	182,000	160,000	18	55	350
0 45	650	1200	130,000	115,000	23	63	250

* Halcomb Steel Company.

pany. It will be noted that these steels compare very favorably with compositions in common use at present, and Houdremont and Bennek[365] in 1932 cited the use of these steels for railroad springs. Although the steels were used for a quarter of a century, very few typical data have been published. As the steels were used only in the heat-treated condition, data on normalized steel are entirely missing although some conception of these properties can be inferred from Kinzel's work.[221]

104. Mechanical Properties of 2 Per Cent Chromium Steel Containing Manganese and Silicon.—Greaves[449] reported a study of the separate and combined effects of manganese and silicon on 2 per cent chromium steel. The effect of manganese in low-silicon chromium steel has been discussed previously

TABLE 76.—MECHANICAL PROPERTIES OF 2 PER CENT CHROMIUM STEEL CONTAINING MANGANESE AND VARIABLE SILICON*

Steel No	Quenching			Tempering†			Tensile strength, lb /sq in	Yield strength, lb /sq in.	Elongation in 2 in , per cent	Reduction of area, per cent	Izod impact value, ft-lb.	Brinell hardness
	Temperature		Cooled in	Temperature		Cooled in						
	°C.	°F		°C	°F.							
2	.		Slowly‡	.			96,500	36,800	24 0	38 0		
3			Slowly				99,100	38,100	24 0	41 0		
4			Slowly			.	102,200	42,600	24 0	41 0		
5	..	.	Slowly	.			103,300	47,500	26 0	43 0		
2	900	1650	Air				131,100	79,400	22 0	59 0	22	
3	900	1650	Air	.	.	.	129,800	77,100	22 0	56 0	21	
4	900	1650	Air				128,000	77,700	22 0	57 0	22	
5	900	1650	Air				131,700	79,800	23 0	56 0	19	
2	1000	1830	Air				137,600	87,400	20 0	55 0	17	
3	1000	1830	Air				140,000	89,600	21 0	55 0	11	
4	1000	1830	Air				135,800	80,600	23 0.	57 0	14	
5	1000	1830	Air				135,300	81,600	20 0	54 0	10	
2	1100	2010	Air				140,200	91,900	18 0	50 0	6	
3	1100	2010	Air				140,400	91,400	18 0	48 0	7	
4	1100	2010	Air				142,700	92,400	18 0	47 0	8	
5	1100	2010	Air				142,700	92,400	20 0	48 0	6	
2	875	1605	Oil	550	1020	Air	168,200	150,100	14 0	48 0	10	376
3	875	1605	Oil	550	1020	Air	172,000	155,000	14 0	46 0	9	361
4	875	1605	Oil	550	1020	Air	174,200	154,000	12 0	45 0	10	358
5	875	1605	Oil	550	1020	Air	182,100	165,000	13 0	44 0	9	373
2	875	1605	Oil	600	1110	Air	160,800	146,200	17 0	51 0	13	332
3	875	1605	Oil	600	1110	Air	159,800	144,200	17 0	53 0	13	327
4	875	1605	Oil	600	1110	Air	161,900	145,300	18 0	50 0	13	331
5	875	1605	Oil	600	1110	Air	157,200	137,400	17 0	46 0	12	324
2	875	1605	Oil	650	1200	Air	125,400	107,700	24 0	63 0	49	261
3	875	1605	Oil	650	1200	Air	129,400	109,800	23 0	61 0	51	269
4	875	1605	Oil	650	1200	Air	131,700	109,300	24 0	61 0	37	269
5	875	1605	Oil	650	1200	Air	133,700	110,300	23 0	58 0	33	273
2	875	1605	Oil	650	1200	Water	150,100	132,200	19 0	58 0	33	319
	875	1605	Oil	650	1200	Furnace	136,300	120,600	19 0	58 0	15	284
3	875	1605	Oil	650	1200	Water	138,900	117,300	21 0	58 0	48	291
	875	1605	Oil	650	1200	Furnace	135,700	117,300	21 0	55 0	17	282
4	875	1605	Oil	650	1200	Water	139,100	112,900	22 0	57 0	43	295
	875	1605	Oil	650	1200	Furnace	135,100	112,500	23.0	55 0	16	279
5	875	1605	Oil	650	1200	Water	144,100	118,600	19.0	54 0	23	304
	875	1605	Oil	650	1200	Furnace	137,200	112,000	22 0	55 0	14	279

* Genders, Davidson, and Marks, according to Greaves.(449)

† Specimens held 2 hr. at tempering temperature.

‡ At the rate of 0 3°C. (0.5°F.) per min.

(page 238). The effect of silicon was determined on steels of the following compositions, forged to $\frac{3}{4} \times 1\frac{3}{4}$ in. bars:

Steel No.	Composition, per cent			
	C	Mn	Si	Cr
2	0 41	0 31	0 40	1 70
3	0 40	0 34	0 67	1.70
4	0.37	0.33	1.05	1 65
5	0.36	0.33	1 32	1.65

Silicon raised the temperature of Ac_1 and Ar_1 2°C. (4°F.) for each 0.1 per cent increase of silicon. The results of tensile and impact tests, shown in Table 76, reveal steel of excellent quality but with very little change due to the presence of silicon. Erratic and very slight increases of strength and lowering of impact resistance were observed. In general, however, silicon seemed to exert no consistent influence. Scaling tests indicated a greater resistance to oxidation in the higher silicon steels at temperatures above 850°C. (1560°F.).

The combined effect of silicon and manganese was investigated in the following series of steels, which were forged from 1.5-in. square ingots to bars 0.9 in. in diameter:

Steel No.	Composition, per cent			
	C	Mn	Si	Cr
6	0.36	0 52	0 70	1 85
7	0 40	0 51	1.05	1 81
8	0 35	0 60	0.35	1 75
9	0 36	0 65	0 98	1 85
10	0 42	0.73	0 75	1 90
11	0.39	0 74	1 25	1 80
12	0.43	0 74	1 40	1.80
13	0.50	0 93	0.24	1 80
14	0.46	0.95	0 43	1 75
15	0.47	0 92	0 73	1 80
16	0.50	1.04	1 10	1 80

TABLE 77.—MECHANICAL PROPERTIES OF 2 PER CENT CHROMIUM STEEL CONTAINING VARIABLE MANGANESE AND SILICON*

Steel No.	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Izod impact value, ft-lb.	Brinell hardness
			Slowly† cooled from 900°C. (1650°F.)			
6	97,500	39,600	22.0	40 0	.	198
7	110,000	45,700	18 0	30 0		220
8	93,600	38,100	23 0	36 0		186
9	103,700	42,100	22.0	34 0	.	211
10	106,100	44,900	17.0	25 0		217
11	117,800	48,400	15.0	25 0		224
12	115,900	51,500	15 0	28 0	.	229
13	112,700	51,100	14 0	20 0	.	223
14	116,200	53,800	13 0	18 0		231
15	115,100	51,100	14.0	19 0		230
16	129,100‡	56,500	....	...	..	243
			Normalized from 1000°C. (1830°F.)			
6	178,700	112,000	20 0	30 0	9	344
7	192,200	114,300	20 0	28 0	10	374
8	158,800	105,300	17 0	36 0	7	318
9	187,700	116,600	20 0	31 0	8	364
10	195,800	123,200	13 0	18 0	6	399
11	§	. . .	3 0	5 0	7	376
12	§	... .	7 0	10 0	6	387
13	§	.. .. .	3 0	4 0	3	404
14	Not machinable					471
15	Not machinable					529
16	Not machinable		.		.	567
			Oil quenched from 875°C. (1605°F) and tempered 2 hr at 650°C. (1200°F.)			
6	132,000	111,200	23 0	62 0	30	273
7	143,900	119,300	22 0	56 0	30	291
8	125,500	104,000	24 0	64 0	69	257
9	138,300	114,800	24 0	58 0	21	284
10	140,200	117,300	22 0	56 0	45	288
11	143,900	117,900	22 0	54 0		298
12	147,900	122,300	21 0	52 0	29	302
13	139,100	117,300	19 0	48 0	29	289
14	142,600	119,800	18 0	45 0	25	294
15	145,100	120,200	20 0	49 0	15	294
16	153,200	128,200	18 0	45 0	12	316

* Genders, Davidson, and Marks, according to Greaves.[449]
† At the rate of 0.3°C. (0.5°F.) per min.
‡ Broke in threads.
§ Broke suddenly during application of load.

Silicon raised and manganese lowered the critical temperatures, about 0.6 per cent manganese compensating for 1.0 per cent silicon. Silicon refined the grain structure and accelerated spheroidization at subcritical temperatures, whereas manganese opposed this tendency. In low-manganese steel, silicon tended to reduce air hardening, but in higher manganese air-hardening steels, silicon increased the hardness. As shown in Table 77, the critical content of manganese for air hardening lay at about 0.50 to 0.60 per cent when the specimens had been normalized from 1000°C. (1830°F.) in the section treated. The alloy additions had little effect on the strength and ductility of quenched and tempered samples but decreased the impact strength in the case of high silicon and increased the susceptibility to temper brittleness in the case of high manganese (Table 78).

TABLE 78.—TEMPER BRITTLENESS OF 2 PER CENT CHROMIUM STEELS CONTAINING MANGANESE AND SILICON, OIL QUENCHED FROM 875°C. (1605°F.) AND TEMPERED 2 HR. AT 650°C. (1200°F.)*

Steel No.	Quenched in water after tempering		Cooled in furnace after tempering	
	Izod impact, ft-lb.	Brinell hardness	Izod impact, ft-lb.	Brinell hardness
1	64	326	28	301
6	55	276	7	264
7	63	293	7	279
8	82	265	12	257
9	45	284	5	272
10	63	288	8	280
11	52	294	4	285
12	34	315	6	299
13	44	299	10	285
14	47	299	9	284
15	41	302	11	286
16	28	319	5	303

* Genders, Davidson, and Marks, according to Greaves.[449]

Although steel of this type has little industrial application, it is apparent that the practical limits of analysis would be at 0.50 per cent manganese and 1 per cent or slightly lower silicon. Although combinations of higher alloy content might be found to have good properties, commercial experience has indicated

that to be assured of safe ductility the borderline compositions should not be approached too closely.

Unpublished work at the Union Carbide and Carbon Research Laboratories, Inc. has shown that the properties of normalized 3 per cent chromium steel are slightly improved by silicon. However, the strength is raised to an extent requiring a lower carbon content for most purposes. For this reason the use of higher silicon in 3 per cent chromium steel does not appear to be economically sound.

C. LOW-CHROMIUM ENGINEERING STEELS CONTAINING NICKEL

Chromium-nickel steels constitute one of the oldest and most widely used classes of low-alloy engineering steels. They have excellent mechanical properties after heat treatment and are used almost entirely in that condition. The compositions commonly used contain two to four times as much nickel as chromium; their properties are essentially those of nickel steel to which chromium has been added to improve the material and lower the cost. For this reason a detailed discussion of the manufacture, properties, and commercial applications is outside the scope of this monograph, and a fuller description will be found in the monograph on "The Alloys of Iron and Nickel."*

105. Manufacture.—A large amount of information has been published on the defects in chromium-nickel steels and methods for controlling them. The reason for this interest appears to lie in the fact that chromium-nickel steels are to a great extent used in large forgings where ingot defects become significantly harmful, rather than in any specifically harmful influence of either chromium or nickel. However, nickel seems to have no restraining influence on the size of primary dendritic crystals so that the alloy additions and deoxidation should be adjusted to correct this condition. Chromium-nickel steels are subject to flakes or hair cracks, as are all of the air-hardening steels; the subject has been well summarized by Greaves.[180] No specific cure has been found, but thorough deoxidation, slow pouring at intermediate temperatures, and slow heating and cooling assist in avoiding flakes. The efficacy of such means of preventing flake formation is not readily accounted for by the current theory relating flake formation to hydrogen evolution. Similar procedures, with

* In preparation.

special reference to cleanliness, are required to avoid woody fractures (see Rapatz[128]). Ingot cracking results primarily from coarse dendritic segregation, and careful deoxidation, pouring practice, and ingot design are required to avoid them.[77,145,185,186] Similar practices are necessary to obtain good mechanical properties in large forgings.[87,433]

In heating for rolling, chromium-nickel steels are not especially subject to overheating and burning, but a thick, tenacious scale is formed which, according to Pfeil,[254] contains a high concentration of metallic nickel in the inner layers, and to a less degree a

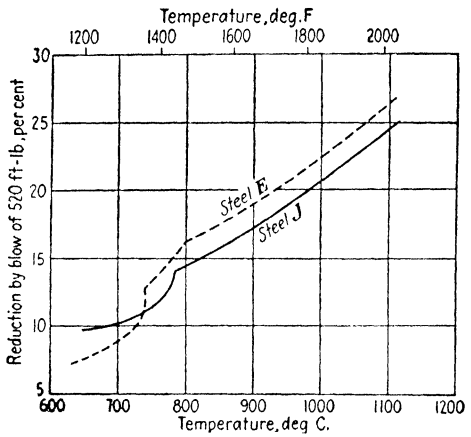


FIG. 106.—Forgeability-temperature curves for a chromium (*J*) and a nickel-chromium (*E*) steel. Steel *J* contained 0.28 per cent carbon, 0.14 per cent silicon, 0.66 per cent manganese, 0.021 per cent sulphur, 0.024 per cent phosphorus, and 0.83 per cent chromium. Steel *E* contained 0 20 per cent carbon, 0 17 per cent silicon, 0.47 per cent manganese, 0.015 per cent sulphur, 0.021 per cent phosphorus, 0.52 per cent chromium, and 1.18 per cent nickel. (*Ellis.*[386])

concentration of chromium oxide. There is also a substantial depth of decarburization. Kothny[87] found that in 4 per cent nickel, 0.5 to 1.0 per cent chromium steels a high forging temperature reduced the fibrous structure, and that sensitivity to overheating was increased with the chromium content. Ellis[386] determined the work necessary for deformation at elevated temperatures and, as shown in Fig. 106, a low chromium-nickel steel was slightly harder than a plain chromium steel. The difference was small and confirms practical experience which has shown that low chromium-nickel steels are not noticeably harder to work than other low-alloy steels. Steels with higher alloy content are inclined to be somewhat stiffer.

Chromium-nickel steels are readily cold drawn, the best annealing temperatures for the higher alloy steels being in the subcritical range according to Pomp and Zapp.[398] The mechanical properties determined by Schneider and Houdremont[148] on a steel containing 0.13 per cent carbon, 0.63 per cent manganese, 0.29 per cent silicon, 0.72 per cent chromium, and 3.66 per cent nickel after cold drawing and subsequent annealing are shown in Fig. 107. They found that on reheating after small reductions softening began at 300°C. (570°F.) and progressed gradually. With higher reductions this temperature was raised to 500°C. (930°F.), and softening became more abrupt. Recovery of the elastic limit in a higher chromium-nickel steel was found by

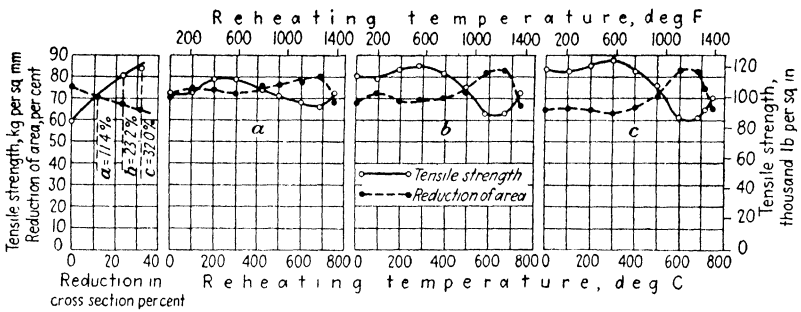


FIG. 107.—Effect of reheating on the tensile strength and reduction of area of a cold-drawn nickel-chromium steel containing 0.13 per cent carbon, 0.63 per cent manganese, 0.72 per cent chromium, and 3.66 per cent nickel. (*Schneider and Houdremont.*[148])

Robertson and Newport[255] to reach a maximum after tempering at 400°C. (750°F.). Lower alloy steels are usually annealed at temperatures above the critical points in order to prepare them for cold working. Relatively small reduction as is used for sizing increases the tensile strength by 10,000 to 20,000 lb. per sq. in., markedly increases the yield strength, and lowers the elongation by one-third to one-half.[418]

106. Heat Treatment.—Thermal studies of chromium-nickel steels have been made by a number of investigators. Jones[111] established that the critical temperatures on heating are determined by the independent tendencies of chromium to raise, and of nickel to lower, the temperature. Andrew, Rippon, Miller, and Wragg[80] investigated the effects of initial temperature, rate of cooling, and reheating on the transformation of austenite.

Both nickel and chromium increase the depth of hardening. The low-alloy grades (1 to 2 per cent nickel and 0.5 to 1 per cent chromium) have hardening characteristics similar to those of other low-alloy steels. With up to 0.40 per cent carbon they are water hardening, and with higher carbon they are oil hardening in moderate sections. The higher alloy grades (3 to 4 per cent nickel and 0.5 to 2 per cent chromium) may be hardened in oil or air depending on composition and section. It is well known that grain size plays an important rôle in the properties of steel and that annealing temperatures should be adjusted to avoid grain growth.

Low-carbon chromium-nickel steels in all grades are used for carburizing purposes. The depth of case after treatment for a given time at a given temperature has been reported by Bullens[195] to be more than might be anticipated from the individual effects of chromium and nickel. The penetration increases with the alloy content. The case tends to change more gradually from outside to core with increase of nickel and tends to become harder with increase of chromium. The lower hardening temperatures made possible by nickel reduce distortion. Considerable care should be exercised in the carburizing and heat treatment of chromium-nickel steel as the steel is not typically fine-grained unless especially deoxidized. The harmful effect of large grains on the strength of the case has been pointed out by McQuaid.[429] Chromium-nickel steel tends to decarburize to a considerable depth and should therefore be heated carefully for hot working as well as for final heat treatment.

107. Mechanical Properties of Chromium-nickel Engineering Steels.—Chromium-nickel engineering steels in common use include the S.A.E. 3100, 3200, 3300, and 3400 series. The ranges of nickel and chromium of these are as follows:

Series	Composition range, per cent		
	Mn	Ni	Cr
S.A.E. 3100	0.50 to 0.90	1.00 to 1.50	0.45 to 0.75
S.A.E. 3200	0.30 to 0.60	1.50 to 2.00	0.90 to 1.25
S.A.E. 3300	0.30 to 0.60	3.25 to 3.75	1.25 to 1.75
S.A.E. 3400	0.30 to 0.60	2.75 to 3.25	0.60 to 0.95

The carbon content ranges from 0.10 to as much as 0.55 per cent; the mean of the specified range of carbon is included with the series number in designating these steels; thus, steel 3240 is a steel of series 3200 with a carbon range of 0.35 to 0.45 per cent. The Society of Automotive Engineers[456] (S.A.E.) has prepared charts* of mechanical properties of many of these steels; these charts "are intended only as a guide to proper heat treatment of the steels and to indicate conservative mechanical properties that may be expected of standard specimens 0.505 by 2 in., machined from rolled bars up to 1.5 in. diameter or square."

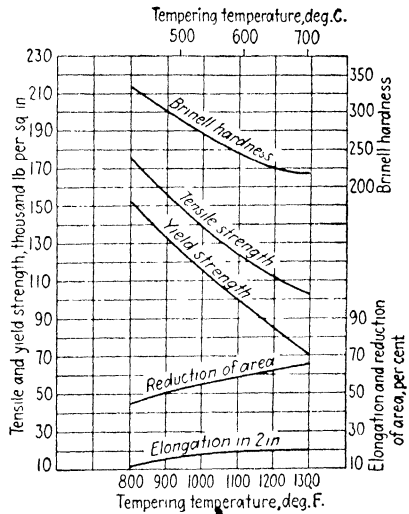


FIG. 108.—Mechanical-property chart of S.A.E. 3140 steel, normalized at 870 to 925°C. (1600 to 1700°F.) and oil quenched from 800 to 830°C. (1475 to 1525°F.). ("*S.A.E. Handbook.*"[456])

There is an enormous amount of data published in the literature and in various handbooks and steel manufacturers' catalogues on the effect of standard heat treatments on the mechanical properties of the S.A.E. chromium-nickel steels. As these will be reviewed and correlated in the forthcoming monograph "The Alloys of Iron and Nickel," it is unnecessary to duplicate this correlation here.

One chart, however, is given. This shows (Fig. 108) the effect of tempering on the mechanical properties of oil-quenched 0.40 per cent carbon, 0.65 per cent manganese, 1.25 per cent nickel, and 0.60 per cent chromium (S.A.E. 3140) steel. It is reproduced to show the susceptibility to heat treatment and the resistance to tempering of this class of steels as well as the mechanical properties of one of the most useful of the commercial chromium-nickel engineering steels, and the general trend of the properties of all of these steels. Carlisle[81] made tensile and torsion tests on three chromium-nickel steels corresponding to S.A.E. series 3300 except that the chromium in heats 1 and 2 was

* "S.A.E. Handbook," 1935, pp. 315–341.

lower than is usual for this grade. The compositions and quenching temperatures were as follows:

Steel No.	Composition, per cent					Quenched in oil from	
	C	Mn	Si	Ni	Cr	°C.	°F.
1	0 34	0 68	0 11	3 50	0.98	845	1550
2*A*	0 42	0 69	0 13	3 75	0 89	825	1515
2*B*	0 42	0 69	0 13	3 75	0 89	845	1550
3*A*	0 30	0 58	0 14	3 28	1 34	825	1515
3*B*	0 30	0 58	0 14	3 28	1 34	845	1550

The tensile and torsional properties after tempering at various temperatures are given in Table 79.

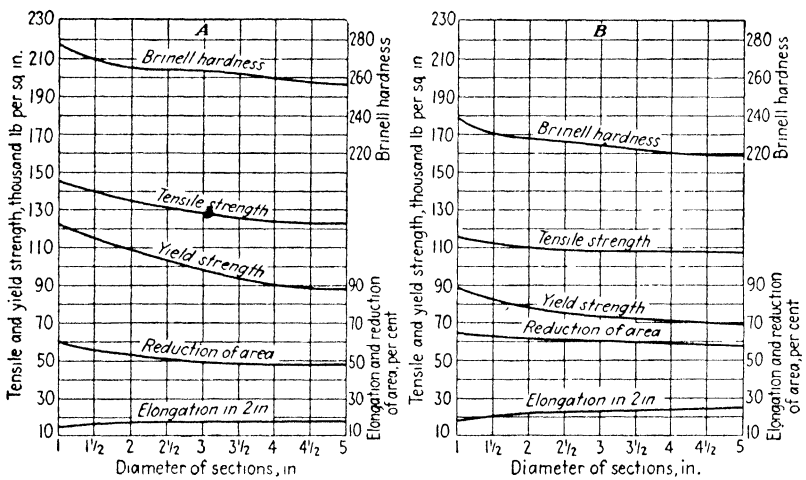


FIG. 109.—Effect of mass on the properties of S.A.E. 3140 steel, normalized at 870 to 925°C. (1600 to 1700°F.), oil quenched from 815°C. (1500°F.), and tempered *A* at 540°C. (1000°F.), *B* at 650°C. (1200°F.). ("*S.A.E. Handbook.*"[156])

108. Effect of Mass on Mechanical Properties.—The effect of mass on the mechanical properties of oil- and water-quenched 3140, 3240, 3340, and 3435 steels after tempering at 540 and 650°C. (1000 and 1200°F.) has been determined and is plotted in the form of charts in the S.A.E. Handbook.* To indicate the trend of properties with increasing cross-section, one of these charts, Fig. 109, has been reproduced here. It will be noted that,

* See footnote, p. 261.

TABLE 79.—TENSILE AND TORSIONAL PROPERTIES OF OIL-QUENCHED AND TEMPERED CHROMIUM-NICKEL STEEL*

Steel No.	Tempering temperature		Tensile tests				Torsion tests			Izod impact value, ft-lb.	Brinell hardness
	°C.	°F.	Tensile strength, lb /sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Torsional strength, lb /sq. in	Yield point, lb./sq. in.	Angle of twist, deg.		
1	540	1005	144,000	128,700	18 0	52 4	113,200	89,200	346	69.0	293
	600	1110	141,400	125,300	18 5	51 7	122,100	80,000	852	63 7	286
	660	1220	. . . .	. . . . .	. .	.	106,400	54,900	652		
2*A*	600	1110	149,400	130,700	21 5	54 4	. . .	. . .	. . . .	50.0	302
	650	1200	148,500	123,800	19 0	47 2	132,000	83,500	1050	54.0	293
2*B*	600	1110	149,700	132,200	19 0	54.3	132,800	92,400	954	53.0	293
	650	1200	146,300	126,000	18 0	48.8	124,000	82,200	886	51.7	293
3*A*	600	1110	145,100	136,100	18.5	54 3	117,100	91,900	884	67.7	286
	650	1200	132,800	110,600	22 0	60.7	112,800	71,900	886	79.7	269
3*B*	600	1110	151,900	142,700	16 5	54.8	126,700	95,800	1094	62.0	311
	650	1200	130,400	112,700	23.0	61 6	112,700	71,300	1104	76 0	262

* Carlisle.[81]

with increasing section, tensile and yield strengths are lowered and reduction of area is also lowered slightly. However, the reduction in these values is much less than would occur with the same increase in mass of a plain carbon steel similarly treated.* Studies by Dickenson,[82] Dawe,[103] Janitzky,[110] Kallen and Schrader,[286] Voss,[404] and others have demonstrated that the low chromium-nickel steels (series 3100 and 3200) are similar to the other low-alloy steels of the S.A.E. series, but that the high chromium-nickel grades (series 3300 and 3400) are superior in depth-hardening capacity. Jones[218] has shown that even very small amounts of chromium and manganese add greatly to the depth-hardening tendency of high-nickel steel.

As the high chromium-nickel steels are used only in massive sections or where extreme toughness is essential, the tendency toward temper brittleness of chromium-nickel steel is usually serious. This type of steel has therefore been made the subject of many studies of this phenomenon although it would appear that chromium-nickel steels are not abnormally susceptible. As discussed in Chapter V, no steel-making, working, or heat-treating practice other than rapid cooling after short tempering periods provides freedom from the defect. All steels appear to be subject to it, but they differ in the rate with which brittleness is developed. As shown in Table 80, Rogers[91] found that chro-

TABLE 80.—TEMPER BRITTLENESS IN HIGH CHROMIUM-NICKEL STEELS*

Steel No.	Composition, per cent					Quenching			Tempering temperature		Izod impact, ft-lb. after	
						Temperature		Medium			Water quenching	Slow cooling
	C	Mn	Si	Ni	Cr	°C.	°F.		°C.	°F		
6	0.40	.	...	3 5	.	830	1525	Oil	600	1110	44	16 5
7	0 25	0 60	0 17	2 72	0 55	800	1470	Oil	600	1110	62	12
8	0 30	0 73	0 17	3 3	0 73	800	1470	Oil	600	1110	41	12
10	0 24	0 43	0 15	3 45	0 95	800	1470	Oil	600	1110	53	11
11	0.30	0 54	0 17	3 5	1 57	825	1515	Air	620	1150	26	8

* Rogers.[91]

mium seems to have a slight tendency to aggravate the condition in high-nickel steels. Greaves and Jones[155] made an extended study of chromium-nickel steel. Manganese and

* See "The Alloys of Iron and Carbon," Vol. II,[478] Chap. VII.

phosphorus increased susceptibility, vanadium had little influence, and molybdenum retarded development of temper brittleness.

109. Effect of Temperature on Properties.—The effects of low temperature are to increase strength slightly and to lower notched-bar impact resistance greatly. As in the case of all quenched and tempered low-alloy steels, chromium-nickel steels retain good impact strength to temperatures of −80 to −100°C. (−110 to −150°F.). As found by Sergeson,[375] these steels in the hardened condition retain good impact strength at somewhat lower temperatures than some other common steels. Langenberg[125] showed that annealed steel is more sensitive than heat-treated steel. Egan, Crafts, and Kinzel[385] and Pilling, in the discussion of their paper, gave Izod and Charpy values, respectively, of S.A.E. 3135 steels in the normalized condition. Both tests indicated comparatively good retention of impact strength down to temperatures of −50 to −80°C. (−60 to −110°F.). A summary including many difficultly available tensile, torsion, fatigue, and impact data was given by Russell.[340] It should be appreciated that the importance of grain size was not recognized at the time the work therein reported was carried out, but even without this newer knowledge, the conclusions drawn are sound.

As pointed out by Bailey, Dickenson, Inglis, and Pearson,[311] the chromium-nickel steels do not have outstanding strength at elevated temperatures. Even in short-time tensile tests the yield strength and tensile strength drop rapidly in high chromium-nickel steels.[107,213] A number of accelerated-creep-test results have been published, but the calculated results are very high. French, Kahlbaum, and Peterson[277] gave limiting creep stresses of 20,500 and 26,000 lb. per sq. in. for a rate of 0.1 per cent in 1000 hours at 375°C. (700°F.) on normalized and tempered billet samples of steels approaching S.A.E. 3135 in composition. Spooner and Foley[346] gave creep data on low chromium-nickel steels as shown in Table 81. White, Clark, and Wilson[443] placed the creep limit for S.A.E. 3140 steel at 540°C. (1000°F.), for 1 per cent in 100,000 hours, at 200 lb. per sq. in. The reported ductility of chromium-nickel steel at elevated temperatures appears to vary according to the conditions of testing but, in general, the steels have good toughness.

Endurance-limit characteristics of chromium-nickel steels have been extensively studied both for specific information on com-

TABLE 81.—RESULTS OF CREEP TESTS OF CHROMIUM-NICKEL STEEL*

Steel No.	Composition, per cent			Quenching			Tempering			Limiting stress, lb./sq. in., for a creep rate of 1 per cent in 100,000 hr. at				
				Temperature		Medium	Temperature		Cooled in	425°C. (800°F.)	450°C. (840°F.)	480°C. (900°F.)	540°C. (1000°F.)	595°C. (1100°F.)
	C	Ni	Cr	°C.	°F.		°C.	°F.						
25	0.42	1 38	0 62	900	1650	Air	600	1100	Furnace	....	6600			
26	0.51	1 65	0 87	825	1515	Oil	625	1155	Air	..	5400			
34	0.35	1.27	0 72	850	1560	Oil	570	1060	Air	13,800	. . .	8900	4300	1800
35	0.39	0.71	0 40	840	1540	Water	600	1100	Air	13,600				

* Spooner and Foley (346)

position and for determination of the general fatigue properties of alloy steel. Moore and Kommers,[113] Gillett and Mack,[137] and Houdremont and Mailänder[247] established that the ratio of fatigue to tensile strength is the same for chromium-nickel as for carbon and other low-alloy steels. Further work by Mailänder[453] demonstrated also that sensitivity to surface condition and shape of specimen is the same for chromium-nickel as for other alloy steels of the engineering type.

110. Other Properties of Chromium-nickel Engineering Steels. The amounts of chromium and nickel used in steels of the engineering grade result in a relatively small degree of corrosion resistance. The greatest advantage in increased corrosion resistance is derived from the relatively heavy and adherent scale found on hot-rolled products. The major applications of chromium-nickel steel, however, do not require corrosion resistance, so that the subject is of little practical interest.

As is true for plain chromium steels, the wear resistance of chromium-nickel steel is relatively good. Although small amounts of nickel do not seem to give any special resistance as does chromium, the high order of toughness of the steels permits use in higher hardness ranges. Many applications, such as gears and dies for which chromium-nickel steels are widely used, depend to a major extent on their high degree of resistance to wear.

Measurements of specific volume of chromium-nickel steels have been made principally to follow the transformation of austenite as shown in Table 82 from Andrew and Honeyman.[133]

TABLE 82 — SPECIFIC VOLUME OF CHROMIUM-NICKEL STEELS QUENCHED FROM 1200°C (2190°F.) IN ICED BRINE AND TEMPERED 1 HR. AT TEMPERATURES SHOWN*

Steel No	Composition, per cent					Quenched	Tempered at			Annealed at 780°C. (1435°F.)
	C	Mn	Si	Ni	Cr		190°C. (375°F.)	365°C. (690°F.)	600°C. (1110°F.)	
						Specific volume, cu. cm. per g.				
B	0.51	0.22	0.13	3.52	1.72	0.12843	0.12814	0.12790	0.12763	0.12763
G1	1.28	0.24	0.15	3.46	1.80	0.12626	0.12626	0.12716	0.12798	0.12788
G2	1.50	0.26	0.19	3.46	1.80	0.12650	0.12647	0.12763	0.12803	0.12791

* Andrew and Honeyman.[133]

It will be noted that, after quenching, steel *B* (0.51 per cent carbon) was largely martensitic, while *G*1 and *G*2 with higher carbon contents contained austenite that was decomposed between 365 and 600°C. (690 and 1110°F.).

It is well known that nickel lowers the modulus of elasticity slightly, and this is carried over into the chromium-nickel steels. Abram[410] in carefully conducted tests found an average Young's modulus of 29,480,000 lb. per sq. in. for steel containing 0.25 per cent carbon, 3.5 per cent nickel, and 0.7 per cent chromium. This may be compared with 30,100,000 lb. per sq. in. for ingot iron, 30,210,000 lb. per sq. in. for a 2 per cent chromium steel, and 29,450,000 lb. per sq. in. for a 3.6 per cent nickel steel.

Thermal conductivity of an S.A.E. 3135 steel was determined by Shelton[436] after normalizing from 900°C. (1650°F.) as follows:

Temperature, °C.	100	200	300	400	500
Temperature, °F.	210	390	570	750	930
Thermal conductivity, watts/cm./°C.	0 445	0 427	0 409	0 391	0 372

Campbell and Dowd[66] found the thermal resistivity relative to ingot iron for a 0.14 per cent carbon, 1.61 per cent chromium, and 4.12 per cent nickel steel to be 2.38 in the annealed condition and 2.68 in the quenched condition. On the same steel the corresponding electric-resistivity values were 32.24 and 34.77 microhms per cu. cm. Campbell and Mohr[177] also measured the electric resistivity and the thermoelectromotive potential (against a purified ingot iron) of a steel containing 0.33 per cent manganese, 0.24 per cent silicon, 1.50 per cent chromium, 3.69 per cent nickel, and carbon varying from 0.02 to 1.41 per cent, as shown in Table 83.

111. Fabrication and Uses.—Although welds by arc or oxyacetylene methods may be readily made in chromium-nickel steels, these steels, except in the form of castings, are ordinarily used in machine parts when welding is not necessary. As in all high-strength steel, welded joints should be stress-relieved or normalized to develop the full properties of the material. Chromium-nickel steel has been used for filler rod, but the carbon content must be kept below 0.35 per cent to obtain good ductility.[335]

Cold shearing and punching may be carried out without difficulty provided the finishing temperature is not too high. Forming is regularly carried out with grades up to S.A.E. 3135, in the rolled condition, but the higher alloy grades should be suitably annealed. The low-alloy, very low carbon steels are suitable for rivets, but the higher carbon and alloy types air harden too readily so that rivets cannot be made tight.

TABLE 83.—EFFECT OF CARBON ON SPECIFIC RESISTANCE AND THERMO-ELECTROMOTIVE POTENTIAL (AGAINST PURIFIED INGOT IRON) OF A STEEL CONTAINING 0 33 PER CENT MANGANESE, 0 24 PER CENT SILICON, 3.69 PER CENT NICKEL, AND 1 50 PER CENT CHROMIUM*

Carbon, per cent	Electric resistivity, at 25°C, microhms per cu. cm		Thermoelectromotive potential, microvolts per °C.	
	Annealed	Quenched	Annealed	Quenched
0.02	32 39	33 11	8 51	8 46
0.10	33 07	34 36	8 91	8.88
0.14	33 98	35 46	9.79	9 24
0.25	35 29	37 64	10 14	9.42
0.34	30 83	40 21	11 59	10 68
0.53	25 46	46 60	13 07	12 93
0.77	29.49	52 55	13 56	15 11
1.05	31 05	57 11	14 31	18 29
1 18	31 97	58 77	14 67	19.27
1 41	34 02	57 60	15 41	18 91

* Campbell and Mohr.[177]

As mentioned in Chapter VI, the machinability of alloy steels has not been well established. The relative machinability of chromium-nickel steels with light cuts (0.0115 in. feed and 0.010 in. depth of cut) was determined by Digges,[317] as shown in Fig. 110. The composition of the steels used is shown on page 270.

The data in Fig. 110 may be compared with the work of French and Digges[178] referred to in Chapter VI. It will be seen that the high chromium-nickel steel was found to have fair machining properties in the range of 200,000 lb. per sq. in., whereas opposite conclusions were reached by Jones.[98] Equally confusing results have been reported by others. In practical machining operations the low chromium-nickel steels offer no particular difficulty, but

Steel	Composition, per cent					
	C	Cr	Ni	Mn	Si	Others
Ni-Cr 3435	0 39	0 76	2 96	0 59	0 26	
Ni-Cr 3140	0 37	0.50	1 26	0 64	0 20	
0 4% C	0 42	.	. .	0 65	0 19	
3.5% Ni	0 36	....	3 43	0 73	0 20	
Cr-V	0 39	0.95	.	0 71	0 20	0 17 V
Cr-Mo	0 39	0.86	. ..	0 56	0 22	0.17 Mo

softening of the high-alloy steels to a commercially machinable hardness requires very careful heat treatment. Even then the

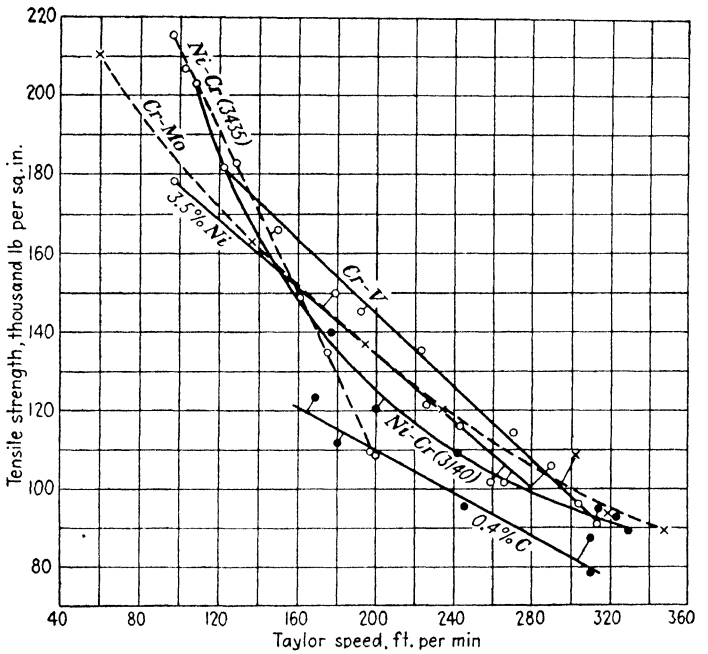


FIG. 110.—Relation of Taylor speed to tensile strength of alloy steels whose composition is given above. (*Digges.*[317])

speed and dimensions of cut must be painstakingly adjusted to avoid tearing and the production of rough surfaces.

The low chromium-nickel steels are used in low-carbon grades for carburized parts such as ring gears, pinions, shafts, transmission gears, piston pins, etc. where a hard case and a tough

core are required. In larger parts or where greater toughness is required, the higher alloy grades are used, as in truck construction. The medium-carbon grades are used for bolts, keys, nuts, shafts, steering knuckles, connecting rods, gears, etc. Highly stressed parts or those requiring extreme toughness, as in aircraft and trucks, require the use of the high-alloy steels. Large forgings such as are used for shafting, pressure vessels, and ordnance also require the use of the very high alloy grades. In the United States the high chromium-nickel steels are used little because of the high cost and difficulty of working, but the low-alloy grades are used in large tonnage for automotive and general uses.

112. Complex Chromium-nickel Steels.—Molybdenum is added in amounts from 0.25 to 1 per cent principally to the high-alloy chromium-nickel steels to decrease mass effect, reduce temper brittleness, and increase high-temperature strength. Typical mechanical properties are shown in Table 84 taken from a study by Andrew, Fisher, and Robertson.[193] It will be noted that molybdenum corrected the temper brittleness.

TABLE 84.—MECHANICAL PROPERTIES AND EFFECT OF MOLYBDENUM ON TEMPER BRITTLENESS OF CHROMIUM-NICKEL-MOLYBDENUM STEELS OIL QUENCHED FROM 860°C (1580°F) AND TEMPERED 3 HR AT 650°C. (1200°F)*

Steel No.	Composition, per cent						Tensile strength,† lb/sq. in	Elongation in 2 in.,† per cent	Izod impact, ft-lb, after cooling from the tempering temperature		
	C	Mn	Si	Ni	Cr	Mo			Slowly	In oil	In water
1	0.37	0.25	0.08	2.02	1.42	0.78	139,000	19.5	45	40	46
2	0.41	0.37	0.12	3.53	1.67	0.89	144,100	19.0	56	40	41
3	0.39	0.33	0.13	5.02	1.59	0.87	150,900	21.0	39	31	28

* Andrew, Fisher, and Robertson.[193]
† Slowly cooled after tempering.

Maurer and Gummert[430] studied the properties of large forgings of a steel containing 0.37 per cent carbon, 0.38 per cent

manganese, 0.23 per cent silicon, 1.15 per cent chromium, 2.96 per cent nickel, and 0.42 per cent molybdenum. Forty-five-ton ingots were cast with basic steel. These ingots, 1430 mm. (56 in.) at the base, 1530 mm. (60 in.) at the top, and 2800 mm. (110 in.) high, were forged to the sections shown in Figs. 111 and 112. After forging, the sections were annealed and cut apart, and a hole the diameter of which was approximately one-tenth the diameter of the forgings was drilled through the axis of each cylinder. After drilling, the cylinders were heat treated as shown. The properties are plotted in Figs. 111 and 112. The data indicate that in general the properties of large forgings of chromium-nickel-molybdenum steel of this composition are excellent, both longitudinally and transversely, throughout the cross-section. These data may be compared with work by the same investigators on low- and medium-carbon steels discussed in a previous monograph.* Spooner and Foley[346] reported for similar steels limiting creep stresses of 13,000 to 25,600 lb. per sq. in. for a creep rate of 1 per cent in 100,000 hr. at 450°C. (840°F.). These values are high for low-alloy steel. Bailey, Dickenson, Inglis, and Pearson[311] reported that steel of this composition had excellent properties up to 550°C. (1020°F.) but that, at that temperature, it crept rapidly under a stress of 3000 lb. per sq. in. A complete summary of published data on chromium-nickel-molybdenum steels to 1932 is given in "The Alloys of Iron and Molybdenum."[360]

High chromium-nickel steel with 0.50 to 1.00 per cent vanadium has been used somewhat in Germany. Smaller amounts of vanadium refine the grain and have a beneficial effect on ductility and impact strength. Mechanical properties of these steels are shown in Table 85.

113. Chromium-nickel Steel Castings.—Although there is some application for steels of higher carbon and alloy contents, the bulk of the chromium-nickel steel castings is made with analyses closely approximating S.A.E. 3135. A number of tests have been reported as shown in Table 86.

This steel appears to be suitable for castings treated to give strengths of 100,000 to 150,000 lb. per sq. in., although a good deal of care is required to obtain good ductility in the higher strength ranges. The effect of larger section has been investi-

* "The Alloys of Iron and Carbon," Vol. II,[478] pp. 217–221, 232, 234–236.

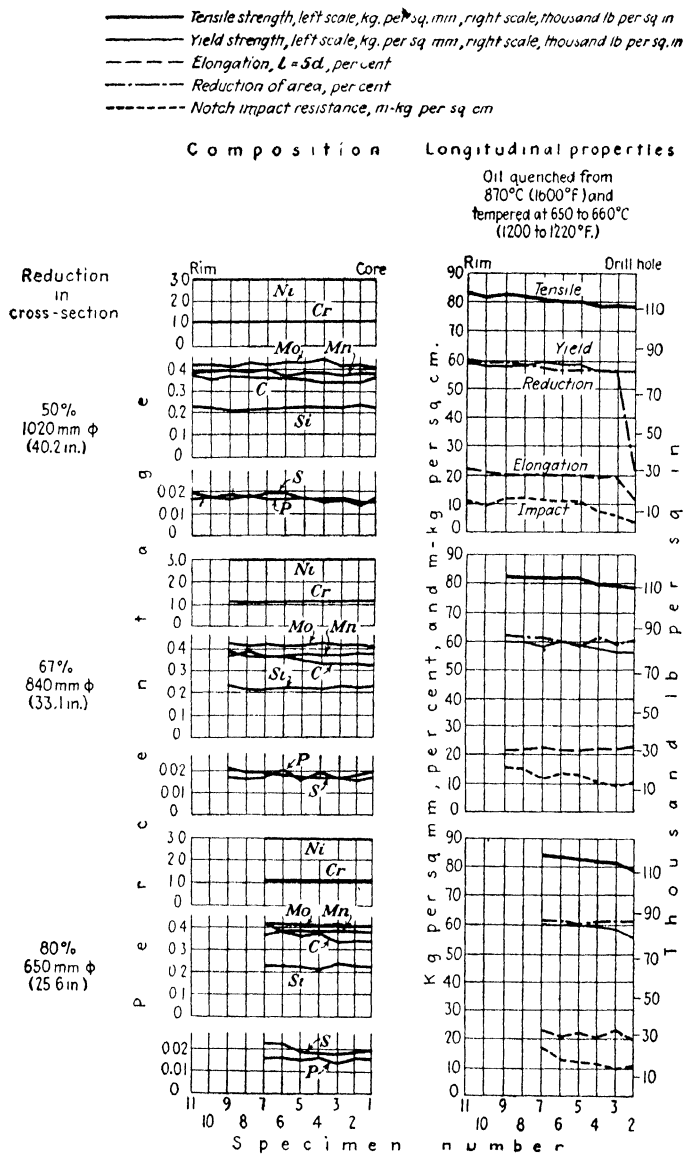


FIG. 111.—Composition and longitudinal properties throughout the cross-section of large forgings with an average composition of 0.37 per cent carbon, 0.38 per cent manganese, 0.23 per cent silicon, 1.15 per cent chromium, 2.96 per cent nickel, and 0.42 per cent molybdenum. Each specimen number represents a section of about 1.5 in. beginning at the core of the forging. (*Maurer and Gummert.*[430])

TABLE 85.—MECHANICAL PROPERTIES OF HEAT-TREATED CHROMIUM-NICKEL-VANADIUM STEEL 5 × 1.5 × 0.75-IN. BARS*

Specimen No.	Composition, per cent					Oil quenched from		Tempered			Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Izod impact, ft-lb.
								Temperature		Cooled in					
	C	Mn	Ni	Cr	V	°C.	°F.	°C.	°F.						
21	0 34	0 18	2 62	0 68	0.36	900	1650	600	1110	Air	149,200	133,100	18.0	....	19 0
						900	1650	650	1200	Air	127,500	113,000	22 0	....	50 0
						925	1700	500	930	Water	154,300	137,200	15 0	52 0	27 0
						925	1700	550	1020	Water	151,900	135,400	17 0	56 0	29 0
						925	1700	600	1110	Water	156,800	139,800	16 0	54.0	22 0
						925	1700	650	1200	Water	130,300	134,200	19 0	63 0	49 0
22	0 36	0 22	2 57	0 64	0 68	900	1650	600	1110	Air	147,400	130,300	21 0	....	21 0
						900	1650	650	1200	Air	128,000	114,100	24 0	...	47.0
						925	1700	500	930	Water	158,600	143,300	15 0	52 0	24.0
						925	1700	550	1020	Water	153,900	139,600	16 0	52 0	26 0
						925	1700	600	1110	Water	154,100	143,000	19 0	56 0	23 0
						925	1700	650	1200	Water	132,800	123,000	19 0	61.0	42.0
24	0 31	0 17	2 63	1 20	0 31	900	1650	600	1110	Air	172,000	163,000	17 0	....	15 0
						900	1650	650	1200	Air	134,800	127,200	23 0	....	44 0
25	0.31	0 21	2 60	1 19	0 34	850	1560	600	1110	Air	167,700	161,900	18 0	55 0	21 0
						850	1560	650	1200	Air	146,100	136,300	20.0	60 0	44 0
						900	1650	600	1110	Air	169,200	158,700	16 0	50 0	16 0
						900	1650	650	1200	Air	135,200	126,700	20 0	58 0	46 0
						920	1690	600	1110	Water	182,200	172,600	15.0	48 0	15 0
						920	1690	650	1200	Water	134,500	123,200	18.0	62.0	40 0
26	0 31	0 20	2 67	1 18	0 61	900	1650	600	1110	Air	178,800	171,000	15 0	....	12 0
						900	1650	650	1200	Air	140,600	132,000	19 0	. . .	36 0

27	0.41	0 22	2 63	1 23	0 37	900	1650	600	1110	Air	179,800	170,200	15 0	...	14 0
						900	1650	650	1200	Air	140.800	134,600	20 0	. .	35 0
28	0.37	0 21	2 66	1 22	0 62	900	1650	600	1110	Air	177,700	171,800	15 0	.	13 0
						900	1650	650	1200	Air	138.800	135,300	20 0	...	36 0
29	0.46	0.20	2.60	1.21	0.65	900	1650	600	1110	Air	185,200	178,500	15.0	....	12 0
						900	1650	650	1200	Air	149,900	143,400	18 0	. .	27 0
32	0 20	0 28	2 84	1 34	0 34	900	1650	600	1110	Air	162.100	154.200	18 0	. .	14 0
						900	1650	650	1200	Air	126,900	119 000	21 0	. .	45 0
33	0 26	0 34	2 82	1 35	0 36	900	1650	600	1110	Air	167,200	160,900	18 0	....	13 0
						900	1650	650	1200	Air	128,900	120,400	21 0	...	42 0
34	0 28	0 43	2 81	1 33	0 34	900	1650	600	1110	Air	167,900	161.700	18 0	. .	12 0
						900	1650	650	1200	Air	127,300	121,100	21 0	.	53 0
36	0 28	0 57	2 75	1 37	0 33	900	1650	600	1110	Air	166,100	158.500	17 0	.	13 0
						900	1650	650	1200	Air	126.900	118,300	22.0	. .	50 0
38	0 34	0 19	5 10	0 61	0 36	900	1650	600	1110	Air	166,300	159,300	18 0		19 0
						900	1650	650	1200	Air	145.300	126.200	19 0	..	34 0
						925	1700	500	930	Water	181,200	177,000	15 0	51.0	18 0
						925	1700	550	1020	Water	178,500	174,000	17 0	55 0	18 0
						925	1700	600	1110	Water	172,900	169,400	17 0	53 0	19 0
						925	1700	650	1200	Water	156,300	142,900	17 0	57 0	29.0
39	0 30	0 20	5 03	0 63	0 61	900	1650	600	1110	Air	181,600	178,800	16 0	....	12.0
						900	1650	650	1200	Air	152,800	133,300	20 0	....	35 0
						925	1700	500	930	Water	182,200	180,200	13 0	50 0	18 0
						925	1700	550	1020	Water	183,800	180,200	14 0	47 0	13 0
						925	1700	600	1110	Water	179,700	177,000	15 0	48 0	14 0
						925	1700	650	1200	Water	161,000	155,800	17 0	55 0	23 0

* Abram.[411]

TABLE 86.—MECHANICAL PROPERTIES OF STEEL CASTINGS CONTAINING 0.35 PER CENT CARBON, 1.00 TO 1.50 PER CENT NICKEL, AND 0.45 TO 0.75 PER CENT CHROMIUM (S.A.E. 3135)

Investigator	Quenching			Tempering			Tensile strength, lb /sq in.	Yield strength, lb /sq in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness	Izod impact, ft-lb.
	Temperature		Medium	Temperature		Cooled in						
	°C.	°F.		°C.	°F.							
Barton[102]	815	1500	Annealed	.	...	.....	66,700	37,000	17 5	25 8		
	730	1350	Annealed	.	.	.....	65,000	32,600	30 1	54 3		
	815	1500	Oil	540	1000	.....	90,000	65,000	23 9	61 6		
	815	1500	Oil	480	900	.. ..	84,400	50,100	26 5	57 7		
Lorenz[126]	815	1500	Air				105,000	75,000	21 0	48 3		
			Air	650	1200	Furnace	106,000	93,000	23 5	52 0	248	37 0
			Water	650	1200	Air	130,000	113,000	14 5	29 5		
			Water	620	1150	Furnace	106,000	92,000	23 0	52 0	248	
			Water	620	1150	Air	107,000	89,000	21 1	51 1	255	44 0
Zuege[264]	900	1650	Air	675	1250	.....	104,000	66,000	22 5	42 0		
			Air	675	1250	.. ...	111,000	70,000	20 5	33 5		
Malcolm[294]	940	1725	Air	610	1130	Air	100,000	65,000	20 0	35 0	200	18 0*
Zima[408]	955	1750		675	1250	Furnace	121,300	95,200	16 0	32 3	248	
	845	1550	Oil	605	1125	.	110,000	78,000	23 0			
Armstrong[381]	855	1575	Water	540	1000	. .	145,600	136,800	14 0	32 1		
	845	1550	Oil	540	1000	.	144,900	132,900	12 2	35 0		
			Oil	510	950		159,000	150,300	10 0	27 3		
			Water†	540	1000	..	155,100	146,700	10 5	32 1		
			Water†	510	950	.	153,800	145,600	11 2	31 1		
			Water	540	1000	..	129,300	115,800	15 2	38 5		
			Water†	540	1000	.	123,800	108,300	17 7	42 6		
	870	1600	Air	540	1000	.	99,800	67,300	22 5	51 5		
Connarroe[447]	Normalized‡			675	1250		102,000	67,400	21 0	41 0		

* Charpy impact.
† Water at 65°C (150°F).
‡ Temperature not given.

gated by Rys[299] on castings from 20 to 400 mm. (0.787 to 15.75 in.) square. The properties shown in Fig. 89 (see Chapter

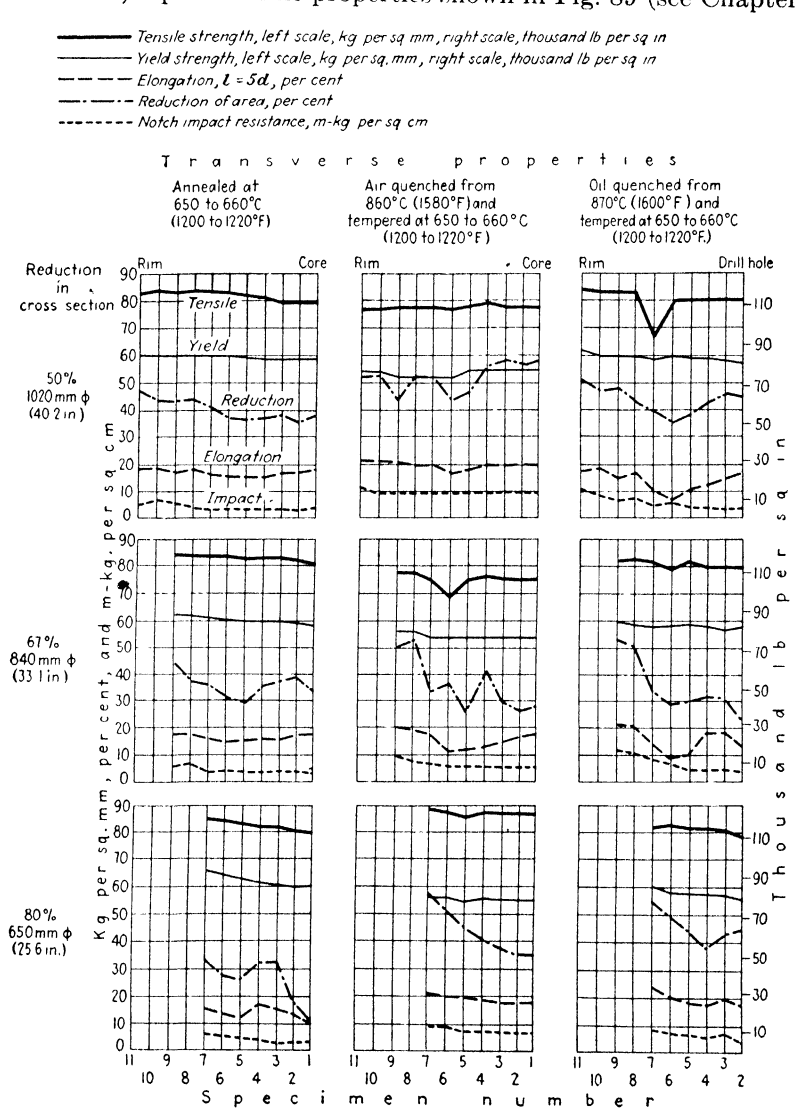


FIG. 112.—Transverse properties of large forgings. See Fig. 111 for composition and longitudinal properties. (*Maurer and Gummert.*[430])

VII, page 200) show a loss of tensile and impact strengths in sections over 120 mm. (4.72 in.). A good review of the high-

temperature characteristics of chromium-nickel steel castings was given by Bull.[314] In general, the strength of castings at elevated temperatures is somewhat better than that of worked material, but otherwise the properties of chromium-nickel steel castings are similar to those of rolled steel. The chromium-nickel-molybdenum steel used for castings also has somewhat better high-temperature strength.

Chromium-nickel steel castings are used for high strength and abrasion resistance in railroad, automotive, agricultural, and general machinery fields. Both plain and with molybdenum they have found moderately wide use in steam and oil-pipe fittings and die blocks where high-temperature strength is required.

D. LOW-CHROMIUM ENGINEERING STEELS CONTAINING COPPER

Although knowledge of the value of copper in steel for corrosion resistance has been available for some time, the development of low chromium-copper steels and their widespread use have come only in recent years. The steel has good properties as heat treated, but it finds its greatest application in high-strength structural material that is used in the rolled or normalized condition. U. S. Patent 1,313,894 was granted to Honhorst in 1919, but industrial development was initiated by Schulz[232] in Germany. While a fairly low ratio of chromium to copper (0.40 to 0.60 per cent chromium, 0.50 to 0.80 per cent copper) has been used in Germany, British and American practices have tended toward the use of 0.60 to 1 per cent chromium and 0.40 to 0.60 per cent copper. Several variations of these analyses are made together with various modifications of the secondary elements such as manganese and silicon. The steels are notable for high strength with good ductility, fabricating properties, and resistance to corrosion.

A comprehensive survey of the published information on chromium-copper steel has been made by Gregg and Daniloff in "The Alloys of Iron and Copper,"[421] so that only a few typical or more recent results are given here.

114. Manufacture and Heat Treatment.—The steels are usually made in the basic open-hearth furnace under the conditions described for plain chromium steels. As reported by

numerous investigators, copper causes surface checking in hot working when present in excess of about 0.40 per cent on account of intergranular penetration of metallic copper in the inner scale layer. The checking may be minimized by heating and rolling at fairly low temperatures and avoiding long-time exposure to oxidizing atmospheres. Nickel is frequently used in the steel in small amounts to prevent the checking. Chromium and manganese also tend to reduce copper checking, and experience has indicated that this defect is practically eliminated in structural chromium-copper steel with 0.6 per cent maximum copper if the total of chromium plus manganese is in excess of 1.35 per cent. Some investigators, however, disagree with this statement. Lorig and MacLaren, whose work was discussed in detail by Gregg and Daniloff,[421] found that manganese and 0.7 to 1.13 per cent chromium have no effect on surface roughening while nickel has a profound effect. An effort should be made to avoid high temperatures and long periods of soaking, and, if suitable compositions and reasonable care are used, the steels are substantially free from surface defects.

As in carbon steel, copper reduces the critical temperatures markedly in chromium steel. On air cooling, copper in excess of that soluble at lower temperatures is retained in solution, but it may be precipitated by tempering in the neighborhood of 500°C. (930°F.) as shown by Buchholtz and Köster,[267] who studied several steels,* one of which contained 0.15 per cent carbon, 0.38 per cent chromium, and 1.1 per cent copper. After air cooling from 800°C. (1470°F.) and reheating, no appreciable change in properties was noted until the reheating temperature was 400°C. (750°F.). After treatment at this temperature, the strength was higher and the ductility lower. The maximum tensile and yield strengths, and the minimum elongation, reduction of area, and impact resistance resulted from reheating to 500°C. (930°F.). Buchholtz and Köster also found that a similar increase in strength resulted from reheating at 500°C. (930°F.) air-cooled sections as large as 300 mm. (11.81 in.) in diameter. Moreover, the properties were uniform throughout the section. It was found further that the strength of cold-worked chromium-copper steel could be increased by precipitation

* The work of Buchholtz and Köster is reviewed in detail by Gregg and Daniloff,[421] pp. 355 to 359.

hardening. This effect is appreciable at 0.50 per cent copper and increases with the copper content.

Chromium-copper steels are similar to chromium-nickel steels in both carburizing and decarburizing tendencies although little commercial application of the steels has been made where these properties are significant.

115. Mechanical Properties.—In 1929 Saklatwalla and Demmler[257] reported the results of a comprehensive investigation on the properties of a series of low-copper chromium steels.* As the data show actual properties of steels containing up to 3.28 per cent chromium and 0.23 to 0.57 per cent copper, they are reproduced here. The composition and heat treatments are given in Table 87, the mechanical properties in Table 88, and the corrosion tests in Table 89. The values shown in Table 88 indicate that the steels have good properties for all ranges of chromium, with tensile strengths up to 100,000 lb. per sq. in. in both the forged and the heat-treated condition.

The mechanical properties of chromium-copper steels, as indicated before, have been adequately summarized by Gregg and Daniloff in "The Alloys of Iron and Copper." Five of the reports of investigations on these steels discussed by Gregg and Daniloff have received brief mention in the present chapter. Jones[285] studied the effect of copper on the properties of two series of steels containing 0.30 per cent carbon, 0.50 per cent manganese, and 0.65 and 0.85 per cent chromium. The results indicated† that increasing the copper to 1.2 per cent improved the tensile and yield strengths of normalized bars of both series.

The low-chromium high-copper steels have been used primarily in Germany. Many investigations on the properties of these steels have been made there to develop the information necessary in connection with the commercial use of these steels. They are made to comply with specification St 52 which requires a minimum yield strength of 36 kg. per sq. mm. (51,200 lb. per sq. in.) and tensile strength of 52 to 64 kg. per sq. mm. (74,000 to 91,000 lb. per sq. in.). Schulz[232] published frequency curves for the values derived from a large number of tests on 18-mm.

* Saklatwalla and Demmler's data on these steels were not reviewed by Gregg and Daniloff[421] as the results do not permit of an evaluation of the effect of copper. *Op. cit.*, p. 376.

† *Op. cit.*, p. 360.

TABLE 87.—COMPOSITION AND HEAT TREATMENT OF STEELS TESTED BY SAKLATWALLA AND DEMMLER[257]

Steel No.*	Composition, per cent						Treatment	Quenching temperature		Cooled in	Tempering temperature	
	C	Mn	Si	Cr	Cu	Ni		°C.	°F.		°C.	°F.
16	0 08		0 24	2 93	0 44		*A*	As rolled				
							B	900	1650	Air		
							C	900	1650	Furnace		
20	0 08		0 84	2 94	0 45		*A*	As rolled				
							B	900	1650	Air		
							C	900	1650	Furnace		
29	0 07		0 84	3 28	0 44		*A*	As rolled				
							B	900	1650	Air		
							C	900	1650	Furnace		
							D	900	1650	Oil	480	900
							E	900	1650	Furnace		
174	0 12		0 03	0 43	0 23		0	As forged				
							1	850	1565	Oil	425	800
							2	850	1565	Oil	600	1110
							3	870	1600	Furnace		
177	0 13	.	0 03	0 49	0 29		0	As forged				
							1	850	1565	Oil	425	800
							2	850	1565	Oil	600	1110
							3	870	1600	Furnace		
233	0 11		0 14	0 55	0 38		0	850	1565	Oil	425	800
							1	855	1575	Oil	540	1000
							2	850	1565	Oil	600	1110
							3	870	1600	Furnace		
172	0 12		0 09	0 59	0 39	.	0	As forged				
							1	850	1565	Oil	425	800
							2	850	1565	Oil	600	1110
							3	870	1600	Furnace		
202	0 11		0 03	0 97	0 23	0 48	1	850	1565	Oil	425	800
							1*a*	855	1575	Oil	540	1000
							2	850	1565	Oil	600	1110
							3	870	1600	Furnace		
116	0 15		0 20	2 88	0 57		1	850	1565	Oil	425	800
							2	850	1565	Oil	600	1110
							3	870	1600	Furnace		
191	0.22	..	0 12	0 90	0 31		1	850	1565	Oil	425	800
							1*a*	855	1575	Oil	540	1000
							2	850	1565	Oil	600	1110
							3	870	1600	Furnace		

TABLE 87.—COMPOSITION AND HEAT TREATMENT OF STEELS TESTED BY SAKLATWALLA AND DEMMLER.[257]—(*Continued*)

Steel No.*	Composition, per cent						Treatment	Quenching temperature		Cooled in	Tempering temperature	
	C	Mn	Si	Cr	Cu	Ni		°C.	°F.		°C.	°F.
115	0.19		0.12	1.66	0.45		1	850	1565	Oil	425	800
							2	850	1565	Oil	600	1110
190	0.25	0.48	0.09	1.73	0.27		1	855	1575	Oil	540	1000
73	0.18	. .	0.07	2.04	0.43		1	850	1565	Oil	425	800
							2	850	1565	Oil	600	1110
							3	870	1600	Furnace		
162	0.24	.	0.34	3.12	0.23		*T*1	720	1330	Water	425	800
							Ta	855	1575	Oil	540	1000
							*T*2	845	1550	Water	720	1330
							*T*3	800	1475	Furnace		
201	0.32	.	0.14	0.46	0.25	0.40	0	As forged				
							1	850	1565	Oil	425	800
							2	850	1565	Oil	600	1110
							3	870	1600	Furnace		
193	0.32	0.55	0.32	0.56	0.28		1	850	1565	Oil	425	800
							2	850	1565	Oil	600	1110
							3	870	1600	Furnace		
166	0.50		0.55	1.53	0.32		3	870	1600	Furnace		
xble 6	0.73	0.41	0.18	1.14	0.45		*Q*	800	1475	Oil	425	800
							A	815	1500	Furnace		
xble 5	1.27	0.65	0.47	1.24	0.51	.	*Q*	800	1475	Oil	425	800
							A	815	1500	Furnace		
xble 8	0.80	0.33	0.22	3.03	0.41		*Q*	800	1475	Oil	425	800
							A	815	1500	Furnace		

* Specimens from heats 16, 20, and 29 *A*, *B*, and *C* were from 20-gage sheet, specimens from 29 *D* and *E* from 1-in. square bars.

(0.709-in.) plate containing approximately 0.15 per cent carbon, 0.80 per cent manganese, 0.25 per cent silicon, 0.40 per cent chromium, and 0.50 to 0.80 per cent copper. Further work was reported by Schulz and Buchholtz[258] and summarized by Gregg and Daniloff.*

The resistance of this low-chromium high-copper steel to aging was studied by Rötscher and Fink.[374] The results, already

* *Op. cit.*, p. 349.

TABLE 88.—MECHANICAL PROPERTIES OF CHROMIUM-COPPER STEELS*

Steel No.	Treatment	Tensile strength, lb /sq in	Yield strength, lb /sq in	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness	Izod impact, ft-lb.
29	*D*	153,800	122,400	14 0	40.7	306	
	E	72,100	40,700	26 0	45 4	148	
174	0	. . .	. .			99	72
	1	60,000	51,500	31 5	66 5	116	70
	2	. .	.			112	82
	3	46,000	43,000	28 0	54 5	99	84
177	0	. . .	. . .			70	81
	1	58,500	46,200	27 5	46 5	149	85
	2	50,500	46,200	13 5	20 5	149	88
	3	. . . .	. . .			109	80
233	0	86,800	62,400	19 3	61 2	. .	48
	1	75,200	46,500	35 0	70 3	143	86.5
	2	79,400	57,200	26 0	68 0		78
	3	62,400	39,900	38 0	71 4	.	65
172	0	. .	.			101	82
	1	60,000	50,000	26 0	59 7	166	84
	2	59,000	54,000	35 0	65 5	166	82
	3	47,600	41,500	38 5	74 5	121	84
202	1	64,800	49,300	27 5	58 3		
	1*a*	69,000	60,300	35 0	75 5	128	90.5
	2	60,000	47,800	36 5	73 3		
	3	57,100	43,200	36 5	74 8	97	93
116	1	67,000	58,500	23 0	51 7	255	24
	2	76,500	60,000	26 0	62 5	223	15
	3	67,500	61,500	24 0	61 0	126	43
191	1	101,500	98,500	8 0	24 5	223	13
	1*a*	107,500	83,100	18 5	49 2	217	56
	2	88,000	80,000	15 0	49 0	223	67
	3	63,300	44,600	26 5	62 2	114	91
115	1	70,000	52,500	23 0	51 5	223	21
	2	65,500	56,200	27 0	57 2	174	56
190	1	156,400	144,400	14 0	45 4	302	2
73	1	139,000	137,000	6 5	18 8		
	2	. . . . .	70,000	22 0	56 2		
	3	. . . . .	35,500	1 0	None		
162	*T*1	173,500	120,000	5 0			
	Ta	164,700	153,400	4 0	3 5	352	
	*T*2	102,000	75,000	17 5			
	*T*3	86,000	42,500	17.5			
201	0	63,300	44,800	4 0	7 5		
	1	111,000	106,000	10.0	24 0	340	5
	2	78,600	49,300	24 5	56 0		
	3	68,000	52,300	24.5	52 3		
193	1	98,500	84,500	19 0	37 0	255	10
	2	80,000	49,200	24 0	52 5	174	78
	3	64,500	49,300	27.5	60 0	146	57
166	3	103,000	102,500	16.5	31.0		
xble 6	*Q*					482	
	A	.				212	
xble 5	*Q*					514	
	A					239	
xble 8	*Q*					505	
	A					212	

* Saklatwalla and Demmler.[257] Composition and heat treatment are given in Table 87.

TABLE 89.—IMMERSION AND SCALING TESTS OF CHROMIUM-COPPER STEELS*

Steel No.	Treatment	Immersion tests, loss in mg. per sq. cm.								Scaling test, gas torch flame, 3 hr at 800°C (1470°F), gain, in mg per sq. cm.
		Water plus oxygen	5 per cent HCl	5 per cent H_2SO_4	5 per cent vinegar	Mine water	Sea water	Water plus carbon dioxide	2 per cent SO_2 in water	
16	*A*	0 02†	8 2	7 1	0 30					
	B	0 15	6 7	4.3	1 7					
	C	0 15	10 9	7 6	4 6					
20	*A*	0 02	9 3	61 5	0 4					
	B	0 08†	2 97	83 3	0 43					
	C	0 26	3 4	67 9	0 48					
29	*A*	0 21	8 08	7 84	0 37					
	B	0 02†	6 89	32 10	0 40					
	C	0 24	8 16	8 39	0 46					
174	0	1 7	7 5	7 6		2 2	0 5	1 4	76 5	8 22
	1	1 2	7 4	5 1		2 5	0 3	1 3	97 0	7 47
	2									8 06
	3	1 2	8 3	3 4		2 0	0 4	5 0	93 5	7 76
177	0	2 3	11 4	4 5		2 7	1 5	2 5	58 6	9 3
	1	0 7	5 4	4 9		2 4	1 0	1 2	64 2	8 70
	2	1 7	4 3	1 9		1 5	0 7	0 9	76 5	8 50
	3	2 0	4 9	4 9		1 9	1 0	1 4	64 3	8 41
172	0	1 5	6 0	3 9		1 6	0 7	1 2	42 5	7 2
	1	8 0	7 8	4 8		1 6	0 6	1 1	58 0	7 45
	2	0 7	4 5	3 7		1 5	0 5	1 0	72 0	8 02
	3	1 2	6 6	4 7		2 2	0 6	0 7	73 5	7 52
xble 6	*Q*	0 04	7 0	9 9	0 5					
	A	0 1	4 9	2 1	0 4					
sble 5	*Q*	0 06	10 7	4 0	0 5					
	A	0 3	10 3	7 6	0 4					
xble 8	*Q*	0 03	7 1	3 3	0 6					
	A	0 02†	7 8	3 3	0 5					

* Saklatwalla and Demmler.[257] Composition and heat treatment are given in Table 87
† Gain.

reviewed,* indicated for the method used (cold deformation by compression, reheating to 250°C. (480°F.), and testing by Charpy impact) that the chromium-copper steel was much more resistant to embrittlement by strain aging than the other steels

* *Op. cit.*, pp. 352, 353.

tested, which included low-carbon basic Bessemer, basic open-hearth, manganese-silicon, and manganese-silicon-copper steels.

Buchholtz and Schulz[313] also studied the fatigue characteristics of this type of steel and found them to be similar to those of other types of structural steel, in both endurance and notch sensitivity.

The higher chromium, lower copper steel sold in England under the trade name "Chromador" contains less than 0.30 per cent carbon, 0.70 to 1.0 per cent manganese, 0.70 to 1.10 per cent chromium, and 0.25 to 0.50 per cent copper. It can be produced with a tensile strength from 71,000 to 96,000 lb. per sq. in. but for structural purposes usually has the following properties:

Tensile strength	83,000 to 96,000 lb. per sq. in.
Yield strength	51,500 lb. per sq. in.
Elongation in 8 in.	17 per cent

Tests on full-size structural members have shown the same strength indicated by tests on small specimens. Suitable steels for rivets have also been developed. Haigh[423] tested 1-in. plate containing 0.26 per cent carbon, 0.74 per cent manganese, 0.11 per cent silicon, 0.93 per cent chromium, and 0.31 per cent copper with the following tensile properties:

Tensile strength	91,800 lb per sq. in.
Yield strength	53,700 lb. per sq. in.
Elongation ($l = 4d$)	30.8 per cent
Reduction of area	66.7 per cent

He determined the fatigue properties under combined steady and alternating loads and found that the endurance limits were of the same ratio to yield strength and tensile strength as in plain carbon steel. Franke[319] reported that this type of steel had non-aging characteristics.

A more recent type of chromium-copper steel is that known in the United States under the trade name "Cor-Ten." The material contains less than 0.10 per cent carbon, 0.10 to 0.30 per cent manganese, 0.10 to 0.20 per cent phosphorus, 0.50 to 1.00 per cent silicon, 0.50 to 1.50 per cent chromium, and 0.30 to 0.50 per cent copper. According to Schramm, Taylerson, and Stuebing,[435] the steel has the following properties:

Property	Sheet	Bar
Tensile strength, lb. per sq. in.	65,000 to 75,000	70,000
Yield strength, lb. per sq. in...	50,000 to 60,000	50,000
Elongation in 2 in., per cent..	27 to 22	27
Izod impact, ft-lb..	.. .	60
Endurance limit, lb. per sq. in.	.	45,000

The ratio of fatigue limit to tensile strength was found to be high. Hot-driven rivets in double shear developed an average shearing value of 81,500 lb. per sq. in. This steel is an excellent example of proper coordination of the alloying elements and a perfect illustration of the thesis that strength obtained without the increase of carbon carries with it exceptional ductility. In this steel, phosphorus partially supplements the effect of carbon and further acts in combination with the other elements to improve corrosion resistance under many conditions. Chromium acts as the major strengthening agent in combination with the carbon and phosphorus, and a moderate addition in strength together with corrosion resistance is obtained from the copper and the high silicon. Bain and Llewellyn[467] have presented a most logical description of the effect of each of the elements in this complex steel and placed special emphasis on its high yield strength. (It should be particularly noted that these effects have been produced with manganese at not over 0.5 per cent. This is definitely in line with the arguments given in the early part of this chapter pertaining to chromium-manganese combinations in rolled or normalized steels.) They further pointed out that the steel is not subject to hardening during the welding process, is readily formed, and that the composition is such that the steel is not unduly sensitive to usual variations in composition or gage.

116. Low-temperature Properties.—The low-temperature impact strength of normalized and water-quenched and tempered steels containing 0.19 per cent carbon, 0.75 per cent manganese, 0.01 per cent silicon, 0.64 per cent chromium, and 1.02 per cent copper was determined by Lequis, Buchholtz, and Schulz.[393] As shown by Gregg and Daniloff,* good low-temperature impact strength was retained to the lowest temperature tested, −80°C.

* *Op. cit.*, pp. 358, 359.

(−110°F.), in all specimens treated to give a strength of less than 100,000 lb. per sq. in.

Steel with higher chromium was investigated by Egan, Crafts, and Kinzel[385] who found that it was particularly well adapted to low-temperature service in the normalized condition. The steel contained 0.10 per cent carbon, 0.24 per cent manganese, 0.24 per cent silicon, 0.83 per cent chromium, and 0.53 per cent copper and was tested in the normalized condition with the following results:

Testing temperature		Izod impact value, ft-lb.
°C.	°F.	
+20	70	85
−50	−60	92
−80	−110	41
−115	−175	13
−185	−300	2 5

The steel was utilized in equipment operating at low temperatures, −80°C. (−110°F.), and further, unpublished, work indicated that somewhat higher chromium and manganese were advantageous in heavier thicknesses of plate.

Izod tests on Cor-Ten steel at −35°C. (−30°F.) showed an impact strength from two to two and one-half times greater than that of carbon steels.[435]

117. Corrosion Tests.—As one of the outstanding advantages of chromium-copper steel is its corrosion resistance, a large number of the workers in this field have made accelerated corrosion tests. Schulz[232] showed it to have excellent resistance to weak sulphuric, formic, and hydrochloric acids. Corrosion tests by Saklatwalla and Demmler,[257] the results of which are given in Table 89, indicate that the chromium-copper steels have increased resistance to oxidizing media with higher chromium content (about 3 per cent) and increased acid resistance with higher copper content (about 0.45 per cent). Schulz and Buchholtz[343] demonstrated that the corrosion-fatigue properties of chromium-copper steels were superior to those of silicon steel, as discussed by Gregg and Daniloff.* Marzahn and Pusch[336]

* *Op. cit.*, p. 351.

found that, in water, acid, caustic, and salt media, copper increased corrosion resistance to a substantial degree and that the further addition of chromium resulted in even greater resistance. These tests were corroborated by similar results on exposure of the steels in a railway tunnel. Substantial corrosion resistance by wet-and-dry tests was found in Chromador steel in acid and brackish water. Speller[437] reported that 0.25 per cent copper usually doubles or triples the life of a steel and that the addition of 1 per cent chromium to a copper steel doubles its life again. On account of the high phosphorus content, Cor-Ten steel is considered to be superior in corrosion resistance to the straight chromium-copper grades.[435]

Although the accelerated tests and the record of similar steels in the past indicate that chromium-copper steels have materially increased life in service, actual tests under industrial conditions are not yet available to judge the type of service that will be most beneficially affected. However, the resistance to abrasion of plain chromium steel would indicate that the greatest benefit will be found where wear is a factor, as in chutes, hoppers, pipes carrying running water, and the like.

118. Fabrication and Uses.—Shearing and punching of chromium-copper structural steels require only the extra power proportionate to the higher strength. Plate having less than 100,000 lb. per sq. in. tensile strength and sheet with higher strength may be readily formed. The lower carbon grades are not air hardening and may be used for high-strength rivets. Full advantage of this high strength may be utilized in riveted structures. In lower strength grades with a tensile strength of 80,000 lb. per sq. in. the steel may be welded by metallic-arc, oxyacetylene, or resistance methods without air hardening, and it is not necessary to heat treat welded structures built of such material except as their dimensions may require stress relieving. In higher strength grades, it is essential that welds be heat treated in order to develop full ductility. Filler rods designed to develop high strength are essential to make the weld as strong as the base plate.

It is apparent from the aforesaid that practically the only wide application of chromium-copper steel is for high-strength structural members. Three grades have come into common use as follows:

Country	Trade name	Composition, per cent					
		C	Mn	Si	Cr	Cu	P
United States...	Cor-Ten	About 0 10	0 10 to 0 30	0 50 to 1 00	0 50 to 1 50	0 30 to 0 50	0 10 to 0 20
Germany	Union	0 12 to 0 18	0 70 to 0 90	0 25 to 0 50	0 40 to 0 60	0 50 to 0 80	
England	Chromador	<0 30	0 70 to 1 00	0 15 to 0 20	0 70 to 1 10	0 25 to 0 50	

These steels are used for bridge, crane, ship, and railroad-car construction where reduction of weight and resistance to corrosion make them decidedly advantageous. In general, design may be based on a stress of 25,000 instead of 16,000 lb. per sq. in.[460] so that substantial savings in weight amounting to 20 to 40 per cent of the structure may be obtained. The high degree of corrosion resistance gives assurance that the lighter sections will not fail on account of corrosion after unduly short service.

E. AUTHORS' SUMMARY

1. The low-chromium engineering steels containing manganese, silicon, nickel, or copper as additional alloying elements constitute a large proportion of the total tonnage of alloy steels used, and include the newer structural steels as well as the older automotive steels. It is evident that improved properties may be obtained in the structural steels by the proper use of chromium in combination with manganese, silicon, or copper. While rolled chromium-nickel structural steels, as distinct from the heat-treated engineering (especially automotive) steels, have not been developed as yet to an appreciable extent, nickel might well be added to the elements just mentioned.

2. Proper proportioning of the alloying elements, including carbon, is important, and the great similarity in the mechanical properties of the various types of chromium-alloy structural steels is striking, with no major difference in ductility for a given tensile-strength range in steels of properly balanced composition. Balanced composition is that composition or range of compositions which, when based upon a specific tensile strength or range of tensile strengths, results in optimum strength-ductility relationships with a given type of heat treatment and cross-section.

3. The chromium-manganese steels referred to in this chapter, with carbon from 0.10 to 0.20 per cent, in the tensile-strength

range of 70,000 to 95,000 lb. per sq. in., are illustrative of balanced steels. For example, 1.25 per cent manganese and 0.5 per cent chromium represents a balanced composition in the normalized state, as does 1 per cent chromium and 0.5 per cent manganese. In the rolled condition, however, optimum ductility-strength relationship does not necessarily occur in these steels unless approximately 0.75 per cent silicon is added to offset the effect of variations in rolling practice. These compositions as well as many others, such as 0.80 per cent manganese and 0.80 per cent chromium, with or without silicon and with or without copper, may be subjected to a suitable heat treatment, resulting in such properties that the compositions may be considered as balanced. If higher strength is involved, such as 90,000 lb. per sq. in., greater care must be taken to obtain a balanced composition in the rolled condition, and here the chromium-manganese-silicon types, with or without copper or phosphorus, are outstanding. However, many other combinations are possible within the scope of the modifying elements treated in this chapter. It is probable that further improved analyses allowing greater economy in manufacture and greater ease in fabrication will be developed in the future.

4. In heat-treated steels, best illustrated by those used in automotive work, the question of balanced composition does not play such an important rôle, as the heat treatment may be adapted to a much wider variety of analyses with resulting optimum mechanical properties. This is particularly true when dealing with tensile strengths up to 175,000 lb. per sq. in. Beyond this tensile strength, the need for carefully balanced compositions again becomes more evident, as the heat treatment becomes more limited in scope. The tensile-strength range up to 175,000 lb. per sq. in. embraces the vast majority of automotive applications including the carburized steels. In this field, the chromium-nickel steels have specific attributes. It is of interest that the mechanical properties of various chromium steels modified with one or more of the elements silicon, manganese, or copper compare favorably with those of the chromium-nickel types. However, the correlative attributes involved in such factors as machinability, lack of distortion on quenching, improved wear resistance, and the like are such that the chromium-nickel steels are preferred for a great many applications in the automotive

field. No detailed discussion of the difference in these correlative factors or of the importance to be given to this difference was held essential. It is necessary to have a specific application in mind before such factors can be evaluated. The rôle of silicon in spring steels may, however, be cited as an example, for it is the same in chromium spring steels as in other types of steels. As measured in the laboratory, the mechanical properties of the chromium-silicon spring steels, with or without additional elements, may be readily duplicated by other types of analyses which do not contain unusual amounts of silicon, but the effect of silicon on the rolled surface, particularly if this be subjected to a quenching treatment, is such as to enhance markedly the fatigue limit, so that the higher silicon steels are always preferred for use in leaf springs.

5. Copper has been used extensively in the structural steels which are used in the rolled condition, because of its mild strengthening effect and its effect in increasing corrosion resistance under certain conditions, particularly when combined with chromium. However, there has been practically no commercial development of copper-containing heat-treated steels, although one might expect a similar improvement in corrosion resistance and although the well-known precipitation-hardening effect of copper might be used to advantage. Conditions of heat treatment and the types of service of the heat-treated articles are such that as yet the use of copper has not been warranted in such steels.

6. The improvement in low-temperature impact strength, particularly in rolled or normalized material, is a specific effect of chromium and copper in combination and is found in steels of medium as well as of fine grain size, being particularly marked in the lower carbon ranges. This improvement is of very real engineering importance not only in the chemical industries but also in transportation where low atmospheric temperatures are encountered.

7. In the modified steels discussed in this chapter, chromium continues in the rôle of ferrite former and carbide former, and is combined with austenite-forming elements and deoxidizers to produce steels with distinctive characteristics. It will be seen from the foregoing that any attempt to point out distinguishing characteristics of these steels when compared with each other

immediately leads to the conclusion that, in general, there are no broad distinguishing characteristics and that marked differences are found only in the various secondary attributes. These, however, may assume primary importance in selecting one or another steel for a given application. This is shown by the innumerable instances where different S.A.E. or low-alloy structural steels are used by different manufacturers to produce articles intended for almost identical service.

8. It is evident, therefore, that the combination of good mechanical properties, relative ease in manufacture, and satisfactorily low cost establishes the status of the low-chromium steels containing manganese, silicon, nickel, or copper, as an important group among modern engineering steels.

CHAPTER IX

LOW-CHROMIUM ENGINEERING STEELS CONTAINING MOLYBDENUM, VANADIUM, OR TUNGSTEN

Low-chromium Engineering Steels Containing Molybdenum—Low-chromium Engineering Steels Containing Vanadium—Low-chromium Engineering Steels Containing Tungsten or Other Alloys—Authors' Summary

Of the three groups of modified chromium steels discussed in this chapter, two—chromium-molybdenum and chromium-vanadium steels—are very important as structural and engineering materials. The former is a comparatively recent development; the first work of importance was published in 1913 by Swinden.[56] It was not until 1926 that molybdenum steels were incorporated into the Society of Automotive Engineers' list of standard alloy steels.

Vanadium steels have been used commercially, especially for springs, gears, and other automotive and railway equipment, for the past 25 years, chiefly because of the grain-refining tendency of the vanadium and the superior toughness that many of the vanadium alloy steels exhibit. Chromium-tungsten steels, containing relatively small amounts of the two alloys, are not used extensively for structural purposes; there are, however, certain engineering applications for which their strength at moderately high temperatures is an advantage.

The recently developed chromium-aluminum-molybdenum nitriding steels are discussed in Chapter XI.

A. LOW-CHROMIUM ENGINEERING STEELS CONTAINING MOLYBDENUM

Molybdenum is commonly used in small amounts (0.10 to 0.75 per cent) to intensify or modify the effect of some other alloying element, in addition to its function *per se*. In chromium steels, molybdenum is added primarily to decrease the effect of mass. This automatically improves the mechanical properties in all but the smallest sections. Molybdenum also confers specific

containing 0.70 to 1 per cent chromium and less than 0.40 per cent molybdenum with carbon varying from 0.15 to 0.52 per cent have been taken from Gregg's discussion and summarized in Table 91. These values show the effect of tempering. All of the steels, except the low-carbon material, were oil quenched. Properties of chromium-molybdenum steels corresponding to *X*4130, 4140, and 4150 after water quenching and tempering were reported by McAdam.[127] Tensile, impact, torsion, and fatigue values are given in Table 92. The compositions of the steels were as follows:

Steel	Composition, per cent				
	C	Mn	Si	Cr	Mo
A	0 39	0 49	0 20	0 76	0 18
B	0 31	0 44	0 22	0 85	0 20
C	0 50	0 48	0 24	1 03	0 19

The mechanical properties of oil-quenched 4140 steel, after tempering at various temperatures, have been plotted in the form of a chart by the Society of Automotive Engineers.[456]* Although the values given in this chart are appreciably lower than those of the corresponding properties given in other published charts for the same steel similarly treated, they may be considered as illustrative of the trend of mechanical properties with tempering temperatures. From the values given in the foregoing discussion, and in the former monograph already cited, it will be seen that the structural chromium-molybdenum steels are not greatly different from the other low-alloy steels as far as the strength-ductility relationship is concerned.

Normalized S.A.E. *X*4130 steel, in thicknesses less than ¼ in., is manufactured with a minimum tensile strength of 90,000 lb. per sq. in. and in this condition fabricated into welded structures. The allowable design stress for fusion-welded joints in the zone affected by the heat is 80,000 lb. per sq. in.

Table 93 from Johnson[284] indicates the type of results that may be expected in heat-treated sheet.

Although relatively little use has yet been made of the higher chromium-molybdenum steels, they have found some application

* "S.A.E. Handbook," 1935, p. 324.

TABLE 91.—SUMMARY OF THE MECHANICAL PROPERTIES OF CHROMIUM-MOLYBDENUM STEELS

Investigator	Composition, per cent				Quenching temperature		Cooled in	Tempering temperature		Tensile strength, lb./sq in	Yield strength, lb./sq.in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness	Izod impact, ft-lb.
	C	Mn	Cr	Mo	°C.	°F		°C	°F.						
Gillett and Mack[154]	0 15		0 73	0 28	925	1700	Water	425	800	155,500	125,000	14 0	55 5	325	53
								525	975	126,300	105,000	18 5	63 9	285	79
								630	1165	97,000	77,500	25 5	78 6	215	117
Mathews in discussion of an article by Hunter[97]	0 31		1 01	0 34	855	1575	Oil	315	600	235,000		12	52	460	10
								425	800	212,000		14	54	420	16
								540	1000	180,000		16	58	365	44
								650	1200	146,000		19	65	285	78
Digges[317]	0 39	0 56	0 86	0 17	885	1625	Oil	260	500	210,900	165,800	6 5	31 8	388	
								370	700	137,200	121,500	18 0	59 4	287	
								480	900	120,700	96,300	18 5	59 5	255	
								595	1100	108,800	76,600	26 5	63 1	204	
								735	1350	93,700	54,300	30 0	60 7	179	
Gillett and Mack[154]	0 40		0 88	0 30	820	1510	Oil	425	800	202,500	170,000	12 0	47 8	420	8
								525	975	166,300	143,000	15 0	52 8	330	26
								625	1155	133,500	111,500	21 0	65 5	290	58
					900	1650	Air			127,000	60,000	17 3	50 1	245	
Gillett and Mack[154]	0 52		0 95	0 39	815	1500	Oil	425	800	209,300	170,000	13 0	47 9	400	16
								525	975	188,300	155,000	17 5	53 9	365	19
								625	1155	135,000	100,000	19 5	55 7	285	72
					900	1650	Air			153,500	50,000	12 0	28 0	300	5

TABLE 92.—MECHANICAL PROPERTIES OF CHROMIUM-MOLYBDENUM STEELS, QUENCHED FROM 870°C. (1600°F.), FURNACE OR WATER COOLED, AND TEMPERED AS SHOWN*

Specimen No.	Cooled in	Tempering temperature		Tensile properties				Charpy impact, ft-lb.	Torsional properties				Endurance limit, lb./sq. in.
		°C	°F.	Tensile strength, lb./sq in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent		Nominal torsional strength, lb./sq. in.	Proportional limit, lb./sq. in.	Degrees twist per linear inch: At yield strength	Degrees twist per linear inch: At breaking strength	
*A*1	Furnace			85,750	48,250	29 0	49 3	8 1	65,200	31,800	26	236	38,500
*A*2	Water	480	900	121,570	86,220	12 7	55 3	11 4	101,900	99,000	82	4	68,000
*A*3	Water	595	1100	136,630	108,500	17 3	61 3	10 5	73,100	55,500	46	140	68,500
*B*1	Furnace			82,430	43,130	27 5	51 7	12 5	62,950	29,560	19	110	36,500
*B*2	Water	480	900	164,750	124,250	13 3	52 3	18 0	104,150	94,180	77	107	72,500
*B*3	Water	595	1100	139,880	116,500	16 0	62 3	12 5	86 040	72,450	60	115	63,500
*C*1	Furnace	..		111,350	50,850	21 0	41 0	4 8	76,700	36,960	30	172	49,500
*C*2	Water	480	900	172,000	128,500	12 3	41 7	12 2	125 510	111,960	81	83	88,000
*C*3	Water	595	1100	157,000	129,000	16 3	55 5	20 7	103,370	81,950	66	103	77,000

* McAdam [127]

for high-temperature strength. In these steels the molybdenum is sufficiently high largely to eliminate temper brittleness after the heating cycles normally used for structural-type steels. The effect of high chromium and molybdenum is shown in Table 94 from Jones.[183] He found that increase of molybdenum over 0.50 per cent gave little benefit, but increase of chromium to 2 per cent was advantageous in the high-strength ranges.

Investigations of the relation between endurance limit and tensile strength have indicated that chromium-molybdenum steels have ratios similar to those of carbon and other low-alloy steels (see Table 92). Tests for shearing properties have also shown no specific effect due to molybdenum.

121. Temper Brittleness and the Effect of Cross-section.—The work of Greaves and Jones[155] on chromium-nickel-molybdenum and of Jones[183] on chromium-molybdenum steels demonstrated that about 0.50 per cent molybdenum effectively stops the development of temper brittleness in normal heat treatment. Later work, notably by Houdremont and Schrader,[391] has shown that the influence of molybdenum is to retard rather than to prevent the development of temper brittleness. Although this is of no significance in steels that are not heated after the initial treatment, it is of the first importance in steels that are to be used at elevated temperatures.

The effect of mass has been studied by several investigators. As shown in Table 95, Dawe[103] found a substantial loss of yield and tensile strengths in a section 2 in. square. However, the ductility increased in proportion to the loss of tensile strength as shown in the table. Janitzky[110] found that 1 per cent chromium, 0.35 per cent molybdenum steel was affected by mass somewhat less than 3 per cent nickel steel, and more than 3 per cent nickel, 0.8 per cent chromium steel. Kallen and Schrader[286] showed that chromium-molybdenum is somewhat superior to plain chromium steel, but neither was particularly good in sections of over 100 mm. (3.9 in.) in diameter. Voss[404] compared a high chromium-nickel with a chromium-molybdenum steel in sections from 60 to 250 mm. (2.3 to 9.7 in.) in diameter and found the chromium-nickel steel to be superior in uniformity across the section. It is evident that molybdenum in chromium-molybdenum steels is sufficiently powerful to correct the mass

effect so that these steels are suitable for small and medium sections; it is, however, not sufficiently effective for very large sections.

TABLE 93.—TENSILE PROPERTIES OF CHROMIUM-MOLYBDENUM (*X*4130) STEEL SHEET AS ROLLED OR QUENCHED FROM 885°C. (1625°F.) AND TEMPERED AS SHOWN*

Thickness, in.	Composition, per cent				Tempering temperature		Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Rockwell *C* hardness
	C	Mn	Cr	Mo	°C.	°F.				
Quenched in oil										
0 039	0 33	0 58	0 91	0 24	As rolled		105,000	90,000	13 0	14
					345	650	210,500	192,000	2 5	47
					480	900	166,500	150,000	5 5	37
					595	1100	150,000	140,000	7 0	32
0 062	0 31	0 58	0 92	0 28	As rolled		100,000	81,000	15 5	16
					345	650	215,000	194,000	4 5	44
					480	900	168,000	156,500	6 5	37
					595	1100	146,500	134,500	9 0	34
0 124	0 30	0 58	0 96	0 25	As rolled		98,000	76,000	18 0	17
					345	650	222,000	206,000	6 8	47
					480	900	169,000	156,000	8 0	40
					595	1100	148,000	139,000	11 0	35
0 25	0 31	0 59	0 98	0 21	As rolled		92,000	61,000	24 5	8
					345	650	222,000	204,000	9 0	47
					480	900	175,000	160,000	12 0	39
					595	1100	150,000	141,000	14 5	35
Quenched in water										
0 039	0 33	0 58	0 91	0 24	345	650	210,000	199,000	2 5	45
					480	900	168,000	157,000	5 5	36
					595	1100	153,000	143,000	6 5	32
0 062	0 31	0 58	0 92	0 28	345	650	212,000	195,000	4 0	46
					480	900	168,000	157,500	6 5	37
					595	1100	151,000	138,000	8 5	34
0 124	0 30	0 58	0 96	0 25	345	650	202,000	191,000	6 0	45
					480	900	170,000	157,000	7 0	39
					595	1100	146,000	134,000	10 0	33
0 25	0 31	0 59	0 98	0 21	345	650	229,000	204,000	9 0	44
					480	900	178,000	165,000	12 5	39
					595	1100	149,000	141,000	14 5	34

* Johnson.[284]

TABLE 94.—PROPERTIES OF CHROMIUM-MOLYBDENUM STEELS OIL QUENCHED AND TEMPERED FOR 2 HR.*

Steel No.	Composition, per cent					Quenching temperature		Tempering temperature		Tensile strength, lb./sq. in.	Elastic limit, lb./sq. in.	Yield strength, lb. sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Izod impact, ft-lb.	Brinell hardness
	C	Mn	Si	Cr	Mo	°C	°F.	°C	°F.							
10	0.33	0.14	0.06	1.08	0.57	900	1650	550	1020	151,000	98,600	127,000	19	52	20	329
						820	1510	550	1020	152,300	100,800	128,800	18	52	21	330
						900	1650	600	1110	141,800	94,100	119,000	17	56	23	310
						900	1650	650	1200	127,500	91,800	106,500	19	64	58	274
						900	1650	670	1240	116,000	80,600	92,800	21	65	67	247
						820	1510	670	1240	117,400	85,100	96,300	23	66	66	250
						900	1650	700	1290	109,600	73,900	88,200	26	67	74	232
11	0.33	0.16	0.07	1.07	1.04	900	1650	550	1020	181,000	134,400	158,600	16	52	18	394
						820	1510	550	1020	181,000	136,600	156,800	17	55	20	385
						900	1650	600	1110	159,700	116,500	136,600	18	55	23	339
						900	1650	650	1200	141,100	114,200	124,000	20	62	49	299
						900	1650	670	1240	133,000	103,000	116,300	21	64	58	285
						820	1510	670	1240	125,200	103,000	112,000	23	62	61	270
						900	1650	700	1290	118,100	98,600	105,300	25	66	70	248
12	0.25	0.32	0.07	1.10	1.38	900	1650	600	1110	155,600	109,800	138,000	19	57	15	341
						900	1650	650	1200	126,600	103,000	111,700	21	62	54	275
						900	1650	670	1240	118,500	94,100	102,400	22	63	60	250
						900	1650	700	1290	111,600	87,300	95,200	25	66	66	236
13	0.26	0.41	0.06	1.58	0.64	900	1650	600	1110	131,700	96,300	113,400	21	62	25	287
						900	1650	650	1200	114,500	85,100	97,400	23	65	54	245
						900	1650	670	1240	106,800	78,400	88,700	23	67	58	230
						900	1650	700	1290	100,200	69,400	80,400	25	69	68	216
14	0.33	0.17	0.06	2.03	0.54	900	1650	550	1020	189,500	147,800	173,700	16	50	19	412
						820	1510	550	1020	189,100	150,100	173,800	16	50	20	411
						900	1650	600	1110	164,000	116,500	147,000	17	55	32	350
						900	1650	650	1200	141,600	105,300	124,500	20	59	46	293
						900	1650	670	1240	134,400	100,800	116,500	22	64	51	283
						820	1510	670	1240	128,600	98,600	109,800	23	64	56	273
						900	1650	700	1290	116,700	82,900	98,600	25	66	63	250

* Jones.[183]

122. Effect of Temperature on Properties.—At low temperatures steel wire containing 0.32 per cent carbon, 0.60 per cent manganese, 0.19 per cent silicon, 1.01 per cent chromium, and 0.43 per cent molybdenum was found by Sykes[149] to increase in strength by about 50,000 lb. per sq. in. between 25 and −180°C., (75 and −290°F.) both as quenched and after tempering. The ductility was reduced in proportion to the rise in strength. Russell[340] reported the properties of a steel with 0.36 per cent carbon, 0.61 per cent manganese, 0.23 per cent silicon, 0.70 per cent chromium, and 0.18 per cent molybdenum at subzero temperatures after full heat treatment. The tests showed a rise of 10,000 lb. per sq. in. in tensile strength at −40°C., (−40°F.), a corresponding rise in Brinell hardness, and a gradual loss of

TABLE 95.—EFFECT OF MASS ON TENSILE PROPERTIES OF A STEEL CONTAINING 0.26 PER CENT CARBON, 0.57 PER CENT MANGANESE, 0.80 PER CENT CHROMIUM, AND 0.36 PER CENT MOLYBDENUM, WATER QUENCHED FROM 845 TO 900°C. (1550 TO 1650°F.) AND TEMPERED AS SHOWN*

Diameter of bar treated, in.	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent
Tempered at 540°C. (1000°F.)				
⅞	158,500	146,900	21.2	55.6
1	162,200	153,900	19.4	55 9
1 5	157,600	147,900	20 3	57.0
2†	125,400	108,500	27 6	62 0
Tempered at 595°C. (1100°F.)				
⅞	137,000	122,700	22 5	60 7
1	129,000	112,400	24 7	64.7
1.5	131,900	118,500	24 0	64 4
2†	117,200	100,500	25 4	66 5
Tempered at 650°C. (1200°F.)				
⅞	118,900	101,000	26.5	68 4
1	117,400	99,300	27.1	66.7
1.5	112,400	92,900	26.9	68 8
2†	100,600	78,800	29 0	70.0

* Dawe.[108]
† Square bar.

impact strength below −40°C. Fatigue tests gave slightly higher values at −40°C. than at room temperature.

It is impracticable to attempt to give the mass of data that has been compiled on the properties of chromium-molybdenum steel at elevated temperatures. A curve of short-time tensile tests on a typical steel containing 0.27 per cent carbon, 0.62 per cent manganese, 0.26 per cent silicon, 0.99 per cent chromium, and 0.41 per cent molybdenum is shown in Fig. 113 from French and Tucker.[122] Tensile, Brinell, and Charpy values at elevated

TABLE 96.—HIGH-TEMPERATURE PROPERTIES OF A STEEL CONTAINING 0.60 PER CENT CARBON, 1.60 PER CENT CHROMIUM, AND 0.22 PER CENT MOLYBDENUM*

Temperature of test		Treatment prior to testing†	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness	Charpy impact, m-kg.
°C.	°F.							
20	70	*A*	130,600	61,000	11 4	26	269	1 0
425	795	*A*	116,400	48,300	10 0	30 6	174	6 8
525	975	*A*	116,400	62,500	14 5	30.0	174	6 0
600	1110	*A*	98,000	48,300	17 0	78 0	127	5 4
700	1290	*A*	56,800	51,200	16 0	65 0	80	27 7
800	1470	*A*	24,400	20,600	29 0	67 0	52	25 6
900	1650	*A*	14,500	8,500	44 0	96.0	25	20 1
1000	1830	*A*	10,200	6,500	50 0	97 0		17 0
20	70	*B*	247,000	. .	.	..	542	0 94
425	795	*B*	201,500	157,600	7 2	30 6	269	2 5
525	975	*B*	170,400	159,000	7 2	44 5	252	4 0
600	1110	*B*	127,800	122,100	10 0	70 0	204	6 5
20	70	*C*	177,000	159,000	9 3	33 0	351	6 95
425	795	*C*	147,600	103,700	11 4	41 0	217	8 0
525	975	*C*	129,200	120,700	11 5	62 0	207	7 0
600	1110	*C*	109,300	103,700	11 4	73 0	...	6 0

* Prulière.[373]

† *A*, annealed at 900°C. (1650°F.), cooled at rate of 50°C. (90°F.) per hr.; *B*, air cooled from 950°C. (1740°F.); *C*, air cooled from 950°C. (1740°F.) and tempered at 600°C. (1110°F.).

temperatures were determined by Prulière;[373] his data are shown in Table 96. The steel contained 0.60 per cent carbon, 0.40 per cent manganese, 0.25 per cent silicon, 1.60 per cent chromium, and 0.22 per cent molybdenum and was tested in the annealed, normalized, and normalized and tempered conditions. It will be noted that chromium-molybdenum steels retain a large portion

of their strength at temperatures up to about 500°C. (930°F.) in short-time tests.

Steels containing approximately 2 per cent chromium and 0.5 per cent molybdenum have found increasing use of late where moderate strength at moderately elevated temperatures is

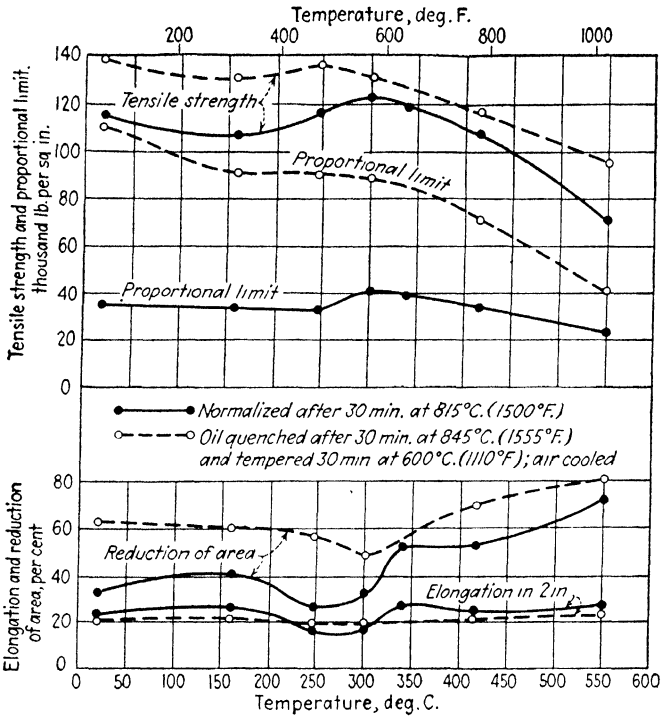


FIG. 113.—High-temperature tensile properties of chromium-molybdenum steel after treatments shown. The steel contained 0.27 per cent carbon, 0.62 per cent manganese, 0.018 per cent phosphorus, 0 008 per cent sulphur, 0.26 per cent silicon, 0.99 per cent chromium, and 0.41 per cent molybdenum (*French and Tucker.*[122])

involved. Such steels have somewhat greater strength and oxidation resistance than those described by Prulière, being intermediate in properties between his steels and the 4 to 6 per cent chromium-molybdenum steels described in Chapter XIII. These same steels containing, in addition to chromium and molybdenum, 1 per cent of silicon possess a creep strength of 15,000 lb. per sq. in., with creep defined as 1 per cent in 100,000 hr., at 540°C. (1000°F.) according to Herzog.[452] Wilson[444] described

a similar steel with 1.25 per cent chromium, 0.50 per cent molybdenum, and 0.75 per cent silicon, as well as a steel with the same silicon and molybdenum contents containing 2.5 per cent chromium, but he gave no creep data.

Another variety of these steels contains 1.7 per cent chromium and 0.70 per cent molybdenum. In a private communication, E. C. Bain cited the following preferred analysis, together with specification range:

Element	Specification range, per cent	Preferred range, per cent
Carbon	0.10 to 0.20	0.13 to 0.18
Manganese	0.40 to 0 60	0.40 to 0 60
Silicon	0.45 to 0.75	0.50 to 0.60
Chromium	1.5 to 2 0	1 6 to 1 8
Molybdenum	0 60 to 0.80	0.60 to 0.80

He recommended normalizing from 870°C. (1600°F.) followed by tempering at 720 to 745°C. (1325 to 1375°F.) and cited the following properties at room temperature:

Tensile strength	75,000 to 85,000 lb. per sq. in.
Yield strength	55,000 to 65,000 lb. per sq. in.
Elongation, in 2 in	23 to 28 per cent
Reduction of area	65 to 70 per cent
Brinell hardness	163 to 192
Fatigue limit (10 million cycles)	40,000 lb. per sq. in.

In connection with use at elevated temperature he gave the following data:

Short-time tensile strength at 480°C. (900°F.)	65,000 to 75,000 lb. per sq. in.
Elongation, in 2 in	15 to 20 per cent
Reduction of area	55 to 65 per cent

The creep strength for 0.1 per cent elongation in 10,000 hr. at 455°C. (850°F.) is quoted as 25,000 lb. per sq. in. minimum, and oxidation resistance is stated to be much greater than that of carbon steels at 540°C. (1000°F.) in 1000-hr. tests. This group of steels is finding increasing use in power-plant piping and to a lesser degree in the petroleum industry.

Creep data reported by Spooner and Foley[346] included an S.A.E. 4135 steel tested by Kanter and Spring in the annealed condition. It was reported to have a limiting creep stress for 1 per cent in 100,000 hr. of 50,000 lb. per sq. in. at 425°C. (800°F.) and of 7500 lb. per sq. in. at 540°C. (1000°F.). A similar steel after oil quenching and tempering was tested by French, Kahlbaum, and Peterson[277] and reported to have a similarly defined creep limit of 41,000 lb. per sq. in. at 425°C. (800°F.) and of 18,000 lb. per sq. in. at 540°C. (1000°F.). Although chromium-molybdenum steels undoubtedly have relatively good creep characteristics, it is felt that the values quoted may have to be revised downward. Similar tests by White, Clark, and Wilson[443] on S.A.E. 4140 steel gave a creep limit of 3700 lb. per sq. in. for 1 per cent in 100,000 hr. at 540°C. (1000°F.). Körber and Pomp,[332] in a study of several types of alloy steels by accelerated methods, found that the ratio of yield-strength values at 20 and 500°C. (70 and 930°F.) was similar for all steels, including chromium-molybdenum, with the single exception that the ratio was higher in the case of nickel-chromium-molybdenum steel. The chromium-molybdenum steels may therefore be considered to have properties that fit them for use at moderately elevated temperatures when the stresses are not too severe.

123. Fabrication and Uses.—Shearing, punching, forming, and other similar operations are usually performed on chromium-molybdenum steel without more difficulty than would be anticipated for any comparable high-strength steel. The lack of sensitivity to finishing temperature gives the steel consistent behavior in these respects. Although broad claims have been made for the machinability of molybdenum-bearing steels, they have not been confirmed by such tests as are available. Certain investigators found that molybdenum steels machined more readily, and others were able to prove exactly the opposite. Similar results appear to have been found in industrial operations. The discrepancy probably is due to lack of appreciation of the rôle of grain size in machinability.

The response to welding of light-gage material for aircraft is one of the outstanding advantages of chromium-molybdenum steels. Welding may be performed by the arc or oxyacetylene method, although the latter is more commonly used on light gages. Whittemore and Brueggeman[307] found that the strength

of butt joints in tension and compression was in excess of 80,000 lb. per sq. in. Beissner[312] found that the fatigue characteristics depended on the quality of the weld and that in good welds the fatigue limit was about two-thirds of the fatigue limit of unwelded tubing. The composition of base metal and welding rod was investigated by Zeyen,[352] who recommended 0.20 to 0.25 per cent carbon, 1.30 to 1.50 per cent chromium, and 0.30 per cent molybdenum steel rather than S.A.E. *X*4130. He also found a 2 per cent chromium-steel rod to give better welds. The type of filler rod has been investigated by several workers, and common practice is to use a plain low-carbon rod for light gages where the thickness of the reinforcement is great enough to compensate for the lower strength, and a high-test rod for thicker sections. In general, the quality rather than the analysis of the rod is the factor that determines the strength of the weld.

The medium-carbon S.A.E. grades of chromium-molybdenum steels are used in automotive, airplane, and general machinery construction for miscellaneous parts such as crankshafts, connecting rods, axles, gears, springs, and drive shafts, and chromium-molybdenum steel has been substituted for other low-alloy steels in many applications. Although occasionally employed as rolled, for structural applications, the steels are ordinarily used in the fully heat-treated condition. Some use of chromium-molybdenum steel is made in heavy shafting, pressure vessels, and railroad forgings, but the depth-hardening influence is not sufficiently great to make this a common application.

One of the outstanding uses of chromium-molybdenum steel is in the form of sheet and tubing for welded construction. The freedom from excessive softening and the moderate air-hardening properties in small sections have made the steel popular for airplane construction. It also has been used to some extent in both light and heavy armor plates.

124. Chromium-molybdenum Steel Castings.—Chromium-molybdenum steels are used in the form of castings for applications requiring abrasion resistance or high-temperature strength. Typical properties are shown in Table 97. The castings are usually normalized and tempered, and in this condition the steel has a relatively high yield strength. Although the addition of the molybdenum makes the less drastic heat treatment more effective, nickel is usually added in castings of large section. The

TABLE 97.—TENSILE PROPERTIES OF CHROMIUM-MOLYBDENUM STEEL CASTINGS

Source	Composition, per cent					Quenching temperature		Cooled in	Tempering temperature		Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent
	C	Mn	Si	Cr	Mo	°C.	°F.		°C.	°F.				
Iron Age[94]	0 27			1 00	0 50	855	1575	Oil	565	1050	148,000	137,500	9.2	29 8
									620	1150	127,500	111,500	16 0	42.6
									675	1250	107,000	85,500	20 0	46.7
									705	1300	106,000	76,000	20 2	52.8
									735	1350	99,500	66,500	21 0	52.6
Grotts[361]	0 39	0 81	0 39	0 69	0 43	Normalized and tempered					103,000	73,000	19.0	40.0
Meissner[226]	0 90	0 45	0.41	1 36	0 30	830	1525	Air	595	1100	156,000	95,000	9.0	9.0
	0 99	0 73	0 60	1 05	0 25	830	1525	Air	595	1100	158,000	89,000	7.0	9.0

effect of mass is shown in Fig. 114 from Rys,[299] which gives properties of steel castings varying from 20 to 400 mm. (0.79 to 15.75 in.) square. The effect of mass became apparent at a section of 120 mm. (4.72 in.). Chromium-molybdenum cast steels are used for grinding and dredging equipment, steam fittings, and hot-working dies and rolls.

B. LOW-CHROMIUM ENGINEERING STEELS CONTAINING VANADIUM

Although vanadium steels have been in use only since 1900, their development has been rapid. Through the grain refinement and enhanced toughening conferred by the vanadium, the first wide engineering application of these steels, aside from tool materials, was in large railroad forgings and castings. With the development of the automobile, advantage was taken of the fact that vanadium allows greater tolerance in steel making and heat treatment. In certain applications, the specific benefits conferred by vanadium in chromium-vanadium steel are sufficient so that it has maintained its position despite competition of other steels, as in springs, gears, large forgings, castings, and high-strength parts that must develop good mechanical properties by normalizing. A large part of the benefit conferred by vanadium may be gained by the addition of less than 0.25 per cent, so that it is usually used in conjunction with another alloy. By far the greatest tonnage has been used in chromium-vanadium steel.

125. Manufacture.—The furnace practice used for chromium-vanadium steel is in general the same as that described in Chapter VI. In open-hearth practice ferrovanadium is added in the ladle with a recovery of about 90 per cent. It is customary to add vanadium to the bath in the electric furnace with practically complete recovery of vanadium. In order not to lose the vanadium content of scrap, the steel is often remelted without oxidation in the electric furnace. Vanadium tends to reduce segregation and dendritic grain size; probably for this reason almost no vanadium engineering steels have been reported to contain flakes.

Chromium-vanadium steels are usually free from ingot cracks and are similar to other low-alloy steels in rolling properties. As shown in Fig. 115, Ellis[386] found that a S.A.E. steel 6130 was somewhat stiffer at low temperatures but was little different at high temperatures from a plain chromium steel of similar analysis.

Andrew and Richardson[445] found that chromium-vanadium billets of spring-steel analysis were scaled and decarburized to a relatively slight degree and there was no penetration of scale

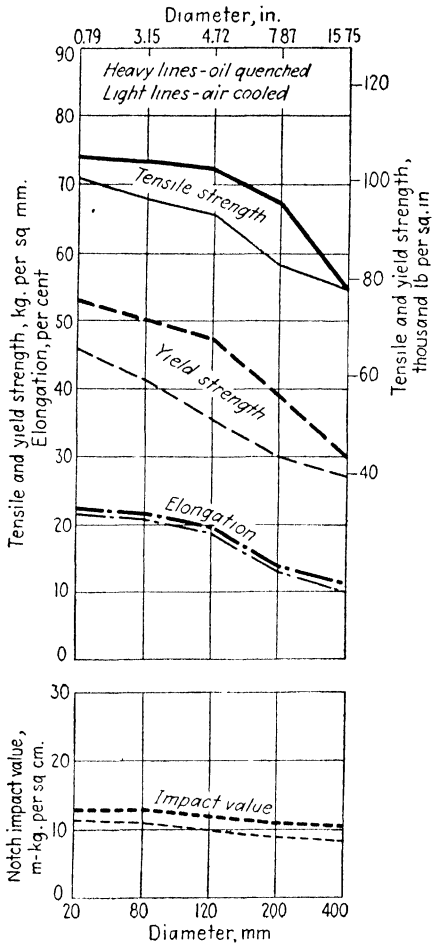


FIG. 114.—Effect of mass on chromium-molybdenum steel castings containing 0.30 per cent carbon, 0.88 per cent chromium, and 0.30 per cent molybdenum. (*Rys.*[299])

along the grain boundaries. Chromium-vanadium steels are not sensitive to variations in finishing temperature within broad ranges, and the ductility of rolled, forged, or hot-formed steel is good enough in many instances to justify their use without further heat treatment.

Cold rolling and wire drawing are readily performed. The usual preliminary treatment is to "patent" the wire at a fairly high temperature. After cold drawing, a temperature of approximately 300°C. (570°F.) is required to restore full elastic properties. Spalding[190] found that cold reduction of hot-rolled 0.27 per cent carbon chromium-vanadium steel from 0.594 to 0.450 in. diameter increased the yield strength by 19,000 lb. per sq. in., the tensile strength by about 5000 lb. per sq. in., and caused only slight

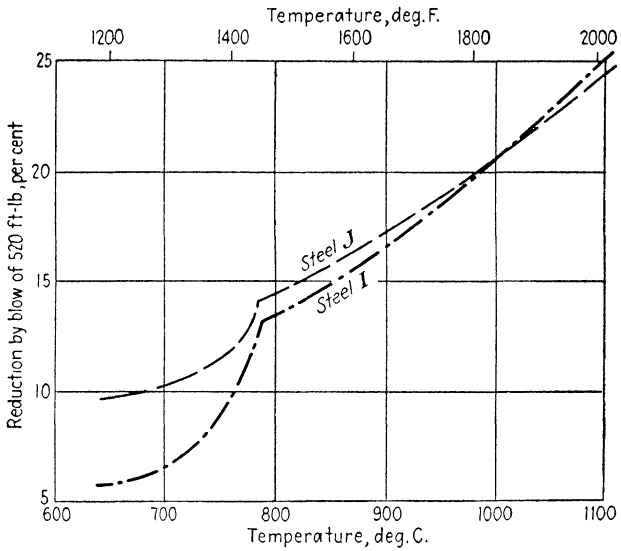


FIG. 115.—Effect of vanadium on the forgeability of chromium steels containing (*I*) 0 29 per cent carbon, 0 17 per cent nickel, 0.90 per cent chromium, and 0.14 per cent vanadium, and (*J*) 0 28 per cent carbon, no nickel, 0.83 per cent chromium, and no vanadium. (*Ellis.*[386])

reduction in ductility. Reheating to 650°C. (1200°F.) was required to destroy the effect of cold working as indicated by tensile strength, impact, and electric resistance. This temperature was found to be relatively high in comparison with manganese and nickel steels.

126. Heat Treatment.—As in carbon steels, vanadium has little effect on the critical temperatures of chromium steels on heating. Vanick and Sveshnikoff[131] found that the addition of vanadium to chromium steels produced very little change. This was confirmed by Abram[411] who reported that in 0.3 per cent carbon steels, up to 0.65 per cent vanadium increased Ac_1 by

8°C. (14°F.) in 0.65 per cent chromium and by 5°C. (9°F.) in 1.2 per cent chromium steels. The end of Ac_3 is not well defined, and in practice it is customary to quench chromium-vanadium steels from somewhat higher temperatures than would be used for similar plain chromium steel. The higher temperature produces no ill effects because of the fine grain of chromium-vanadium steel.

On cooling, the effect of vanadium is to raise the critical temperatures and make steel shallow hardening. It is probable that the true influence of vanadium is in the other direction and that the shallow-hardening tendency results from the fine grain. On reheating after quenching, a secondary hardening takes place at 500 to 600°C. (930 to 1110°F.) which was found by Hohage and Grützner[141] to produce a constant strength within that tempering range. This phenomenon was also studied by Houdremont, Bennek, and Schrader[366] who attributed it to the precipitation hardening of ferrite by vanadium carbide. They also found that steels hardened and tempered in this range were relatively insensitive to the effect of mass. In practice, the composition and treatment should be adjusted so that advantage may be taken of the small variation of strength with tempering temperature. On account of the rapid softening, tempering at higher temperatures should be avoided.

While the fine grain size of chromium-vanadium steel is desirable in the final product, it is advantageous for many machining operations to have a coarse grain. McQuaid[429] has shown that coarse grain may be produced in chromium-vanadium steels by normalizing from above 925°C. (1700°F.), whereas steels made fine by special melting treatments usually require temperatures of 980 to 1040°C. (1800 to 1900°F.).

Chromium-vanadium steel has a rate of penetration in carburizing that is not quite so high as that of the nickel-bearing steels. The carbon content of the surface is high and the carbides are suitably dispersed for toughness and wear resistance. The fine grain reduces distortion and the steel finds considerable application for case-hardened parts such as gears and the like. Decarburization characteristics of chromium-vanadium steel are similar to those of plain chromium steel but, as most of the tests have been carried out on spring steels, decarburization is discussed further in that connection.

With the exception of steels for special purposes, the commonly used grades approximate closely the specifications set up by the Society of Automotive Engineers.[456] In the "S.A.E. Handbook" the chemical specifications are shown as reproduced in Table 98.

TABLE 98.—CHEMICAL SPECIFICATIONS FOR ORDINARY S.A.E. CHROMIUM-VANADIUM STEELS*

S.A.E. No.	Composition, per cent				
	Carbon	Manganese	Chromium	Vanadium	
				Minimum	Desired
6115	0 10 to 0.20	0 30 to 0 60	0 80 to 1 10	0 15	0 18
6120	0 15 to 0 25	0 30 to 0 60	0 80 to 1 10	0 15	0 18
6125	0 20 to 0 30	0 60 to 0.90	0 80 to 1 10	0 15	0 18
6130	0 25 to 0 35	0 60 to 0 90	0 80 to 1 10	0 15	0 18
6135	0 30 to 0 40	0 60 to 0 90	0 80 to 1 10	0 15	0 18
6140	0 35 to 0 45	0 60 to 0.90	0 80 to 1 10	0 15	0 18
6145	0 40 to 0 50	0 60 to 0 90	0 80 to 1 10	0 15	0 18
6150	0 45 to 0 55	0 60 to 0 90	0 80 to 1 10	0 15	0 18

*"S A E Handbook."[456]

The treatments recommended for the carburizing grades are as follows:

Heat treatment No. 1 for steels 6115 and 6120:

1. Normalize at least 30°C. (50°F.) above the carburizing temperature.
2. Carburize at 900 to 925°C. (1650 to 1700°F.).
3. Quench directly from the box.
4. Reheat to 775 to 800°C. (1425 to 1475°F.) for case hardness only, or reheat to 800 to 830°C. (1475 to 1525°F.) for core hardness.
5. Quench in oil.
6. Temper at 120 to 175°C. (250 to 350°F.).

Heat treatment No. 2 for steels 6115 and 6120:

1. Normalize at least 30°C. (50°F.) above carburizing temperature.
2. Carburize at 900 to 925°C. (1650 to 1700°F.).
3. Cool slowly or in the box.
4. Reheat to 775 to 800°C. (1425 to 1475°F.) for case hardness only, or reheat to 800 to 830°C. (1475 to 1525°F.) for core hardness.
5. Quench in oil.

6. Temper at 120 to 175°C. (250 to 350°F.).

Heat treatment No. 3 for steels 6115 and 6120:

1. Normalize at least 30°C. (50°F.) above carburizing temperature.
2. Cool slowly or in the box.
3. Reheat to 870 to 900°C. (1600 to 1650°F.).
4. Quench in oil.
5. Reheat to 775 to 800°C. (1425 to 1475°F.).
6. Quench in oil.
7. Temper at 120 to 175°C. (250 to 350°F.).

Heat treatment No. 4 for steels 6115 and 6120:

1. Heat to 815 to 900°C. (1500 to 1650°F.) in cyanide or activated bath.
2. Quench in oil.
3. Temper if desired.

Parts "cased" in activated baths may be given the refining treatments as indicated in heat treatments Nos. 1, 2, and 3.

The heat treatments for the higher carbon structural and engineering grades are as follows:

Heat treatment No. 1 for steels 6125 and 6130:

1. Heat to 855 to 885°C. (1575 to 1625°F.).
2. Quench in oil or water.
3. Temper to attain the required hardness.

Heat treatment No. 2 for steels 6125 and 6130:

1. Normalize at 900 to 955°C. (1650 to 1750°F.).
2. Heat to 855 to 885°C. (1575 to 1625°F.).
3. Quench in oil or water.
4. Temper to attain the required hardness.

Heat treatment No. 1 for steels 6135 and 6140:

1. Normalize and anneal to attain the desired structure for machinability.
2. Heat to 845 to 900°C. (1550 to 1650°F.).
3. Quench in oil.
4. Temper to attain the required hardness.

Heat treatment No. 1 for steels 6145 and 6150:

1. Normalize and anneal to attain the desired structure for machinability.
2. Heat to 830 to 885°C. (1525 to 1625°F.).
3. Quench in oil.
4. Temper to required hardness (388 to 444 Brinell, for leaf springs).

127. Mechanical Properties of the Low-carbon Grades (6115 and 6125).—The properties of a steel corresponding to S.A.E. 6115

were reported by Vanick[115] as shown in Table 102, page 320. This steel is used primarily for carburizing, and after carburizing and hardening the case has a high strength as shown in Table 99 by McQuaid.[429] In grades corresponding to S.A.E. 6125 the steel is strengthened by air cooling or by water hardening as shown in Table 100 from Griffiths[68] and in Table 101 from Bullens.[195] The steels used by Bullens had the analysis shown in the table at the top of page 316.

TABLE 99.—PROPERTIES OF THE CASE OF CARBURIZED AND HEAT-TREATED 6115 STEEL CONTAINING 0.15 PER CENT CARBON, 0.45 PER CENT MANGANESE, 0.20 PER CENT SILICON, 1.00 PER CENT CHROMIUM, AND 0.15 PER CENT VANADIUM, CARBURIZED AT 925°C. (1700°F.)*

Specimen	Treatment after carburizing†	Strength of case at appearance of first crack, lb./sq. in.	Deflection, in.	Case depth, in.
1	Quenched from pot	191,200	0 114	0 028
2	Quenched from pot	172,200	0 090	0 050
3	Quenched from pot	170,900	0 082	0 066
4	Quenched from pot	158,400	0 080	0 080
5	Quenched in oil from 885°C. (1625°F.)	200,400	0 115	0 039
6	Quenched in oil from 885°C. (1625°F.)	210,700	0.129	0.056
7	Quenched in oil from 885°C. (1625°F.)	192,800	0 105	0.065
8	Quenched in oil from 885°C. (1625°F.)	208,500	0 113	0 080
9	Quenched in oil from 900°C (1650°F.)	170,900	0 128	0.034
10	Quenched in oil from 800°C (1475°F.)	170,100	0 096	0 056
11	Quenched in oil from 800°C (1475°F.)	196,000	0 119	0 060
12	Quenched in oil from 800°C. (1475°F.)	202,900	0 121	0 078

* McQuaid.[429]

† All steels were tempered 1 hr. at 160°C. (325°F.) after quenching

Steel 6125 can be oil hardened but a higher quenching temperature is required (see Table 101). The steel is characterized by an especially high reduction of area with good, but not exceptional,

Mark or description	Composition, per cent				
	C	Mn	Si	Cr	V
A	0 26	0 48	0.06	0 92	0 20
D	0.50	0.92	0 07	1 02	0 20
G	0 60	0 54	0.18	0 88	0 19
H	0.23	0 58	0.11	0 82	0.17
Tender axle	0 29	0 28	0.06	1 00	0 20
Locomotive drive axle	0 35	0.50		0 90	0 22

elongation. A chart given by Norris[473] (Fig. 116) shows the properties of 6125 steel graphically. The nearly constant

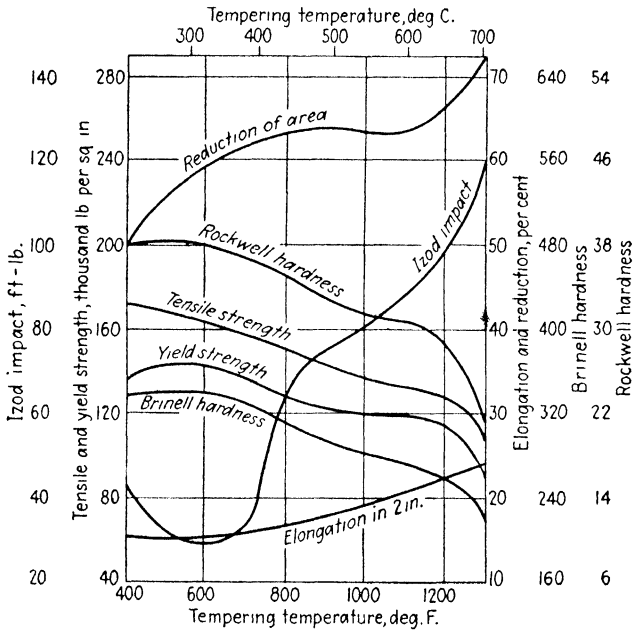


FIG. 116.—Mechanical properties of 1-in. round bars of S.A.E. steel 6125, normalized at 900°C. (1650°F.) and water quenched from 885°C (1625°F.). The steel contained 0.23 per cent carbon, 0.27 per cent silicon, 0 75 per cent manganese, 0.96 per cent chromium, 0.17 per cent vanadium, 0.019 per cent phosphorus, and 0.033 per cent sulphur. (*Norris.*[473])

strength at tempering temperatures between 540 and 620°C. (1000 and 1150°F.) should be noted. With tempering temperatures of 425°C. (800°F.) or over, the impact strength is high. Mathews, in discussion of a paper by Hunter[97] (see also Table 91,

page 297), considered that the low impact strength of chromium-molybdenum steel after tempering at about 315°C. (600°F.) is typical of all heat-treated steels. It will be seen that this is true of S.A.E. 6125.

TABLE 100.—EFFECT OF TEMPERING ON MECHANICAL PROPERTIES OF 6125 STEEL,* CONTAINING 0.24 PER CENT CARBON, 0.69 PER CENT MANGANESE, 1.10 PER CENT CHROMIUM, AND 0.15 PER CENT VANADIUM†

Specimen No.	Tempering temperature		Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness
	°C.	°F.					
1	200	390	209,000	194,000	12 0	51 0	444
2	260	500	206,000	197,000	11 1	53 0	444
3	320	610	198,000	182,000	10 0	53 0	444
4	375	705	179,000	166,000	13 0	57 0	402
5	430	805	169,000	161,000	15 0	58 0	387
6	485	905	157,000	148,000	16 0	59 0	364
7	540	1005	155,000	144,000	18 0	60 0	340
8	595	1105	142,000	130,000	20 0	63.0	332

* The steel was heated to 850°C (1560°F), cooled very slowly to 800°C. (1470°F), and quenched in water; then tempered 20 min. at temperatures shown and cooled in air.
† Griffiths [68]

128. Mechanical Properties of the Medium-carbon Grades (6130, 6135, 6140).—Steels with somewhat higher carbon content were also studied by Vanick.[115] The properties of these are reproduced in Table 102. In addition to giving properties of steels of the standard S.A.E. compositions, he showed that increase of vanadium raised the strength for a given heat treatment over a wide range of quenching temperatures, and for this reason it is difficult to estimate the effect of vanadium on ductility, although the higher vanadium steels have the characteristically high reduction of area. Vanadium had little influence on the hardness of annealed steel. Increase of chromium to 2 per cent caused a progressive increase in yield strength, but the small section treated masked any evidence of greater depth-hardening capacity. Somewhat similar tests by Abram[411] were made on material of the analysis shown in the table on page 319. The results, reproduced in Table 103, show the effect of increasing the vanadium from 0.38 to about 0.65 per cent, on steels containing 0.65 and 1.20 per cent chromium. As found by

TABLE 101.—MECHANICAL PROPERTIES OF HEAT-TREATED CHROMIUM-VANADIUM STEELS*

Specimen No.†	Quenching temperature		Cooled in	Tempering temperature		Tensile strength, lb /sq. in	Yield strength, lb /sq. in	Elongation in 2 in., per cent	Reduction of area, per cent
	°C.	°F.		°C.	°F.				
*A*1	As rolled		..	..	.	132,000	110,000	19 0	51 5
*A*2	800	1475	Furnace		.	83,700	61,000	34 8	66 4
*A*3	850	1560	Oil	400	750	173,900	149,800	13 0	57 0
*A*4	850	1560	Oil	450	840	171,100	147,150	15 0	61 0
*A*5	850	1560	Oil	500	930	156,800	138,440	16 5	59.8
*A*6	850	1560	Oil	550	1020	137,500	112,750	21 0	64 5
*A*7	850	1560	Oil	600	1110	133,000	108,400	17 5	65 4
*A*8	850	1560	Oil	625	1155	131,000	100,000	28 0	67 0
*A*9	900	1650	Oil	400	750	183,500	155,000	13 0	51 0
*A*10	900	1650	Oil	450	840	177,500	151,500	14 0	53 0
*A*11	900	1650	Oil	500	930	162,700	146,000	15 0	57 0
*A*12	900	1650	Oil	550	1020	141,500	123,000	18 0	63 5
*A*13	900	1650	Oil	600	1110	137,000	112,000	20 0	61 0
*A*14	900	1650	Oil	625	1155	133,000	99,020	30 0	69 9
*A*15	850	1560	Water	450	840	201,800	172,800	12 5	54 5
*A*16	850	1560	Water	500	930	176,950	165,000	14 0	59 0
*A*17	850	1560	Water	550	1020	166,800	149,100	14 0	58 9
*A*18	850	1560	Water	600	1110	156,500	146,300	17 0	61 0
*A*19	850	1560	Water	625	1155	153,050	136,600	27 0	60 0
*A*20	900	1650	Water	450	840	204,800	176,200	12 5	54 5
*A*21	900	1650	Water	500	930	183,200	166,800	12 5	56 5
*A*22	900	1650	Water	550	1020	167,800	151,000	12 0	53 6
*A*23	900	1650	Water	600	1110	160,900	149,700	16 0	60 4
*A*24	900	1650	Water	625	1155	156,000	133,000	18 0	62 5
*D*1	As rolled				.	153,350	124,450	12 5	37 0
*D*2	800	1475	Furnace			103,440	63,660	25 8	61 5
*D*3	825	1520	Oil	400	750	260,500	240,000	8 0	24 0
*D*4	825	1520	Oil	450	840	237,750	213,400	10 0	35 5
*D*5	825	1520	Oil	500	930	215,450	193,100	12 0	41 5
*D*6	825	1520	Oil	550	1020	183,500	177,250	14 5	47 5
*D*7	850	1560	Oil	400	750	261,850	240,000	7 0	22 0
*D*8	850	1560	Oil	450	840	234,150	215,850	9 0	28 5
*D*9	850	1560	Oil	500	930	214,270	201,400	11 5	36 0
*D*10	850	1560	Oil	550	1020	197,100	187,100	12 5	45 0
*D*11	870	1600	Oil	450	840	237,500	221,000	10 0	29 5
*D*12	870	1600	Oil	500	930	214,050	203,600	11 5	43 0
*D*13	870	1600	Oil	550	1020	205,500	187,000	12 0	45 0
*D*14	870	1600	Oil	600	1110	186,100	161,200	13 5	45 5
*D*15	900	1650	Oil	400	750	264,500	239,700	6 5	17 0
*D*16	900	1650	Oil	450	840	227,040	217,360	10 0	35 5
*D*17	900	1650	Oil	500	930	209,800	192,200	12 5	42 5
*D*18	900	1650	Oil	550	1020	201,150	186,100	13 0	45 5
*D*19	900	1650	Oil	600	1110	186,800	170,000	15 5	45 2
*G*1	900	1650	Oil	400	750	273,000	248,660	8 0	27 3
*G*2	900	1650	Oil	500	930	240,400	220,000	10 0	28 3
*G*3	900	1650	Oil	600	1110	205,190	179,300	13 0	37 0
*H*1	900	1650	Oil	565	1050	124,950	107,430	19 5	60 5
*H*2	900	1650	Oil	565	1050	124,750	108,230	18 8	55 0
*H*3	900	1650	Oil	565	1050	122,610	106,750	18 3	60 9
6-in. tender axle	920	1690	Water	625	1155	115,000	90,000	21 0	55 0
10-in locomotive drive axle	920	1690	Water	625	1155	108,890	81,600	21 75	58 75

* Bullens.[196]

† Specimens *A* and *D* were small sections, probably under ¾ in. round. Specimens *H*1, *H*2, and *H*3 were 2½-, 2⅝-, and 2¾-in. sections.

Steel No.	Composition, per cent			
	C	Mn	Cr	V
10	0 30	0 19	0 65	0.39
11	0 36	0.19	0 63	0 63
13	0 36	0 21	1 20	0 38
14	0.34	0.21	1 20	0.68

Aitchison[93] the secondary hardening was more pronounced with 0.35 than with 0.15 per cent vanadium. The impact strength was higher with 1.20 than with 0.65 per cent chromium in the section tested ($\frac{3}{4} \times 1\frac{1}{2}$ in.).

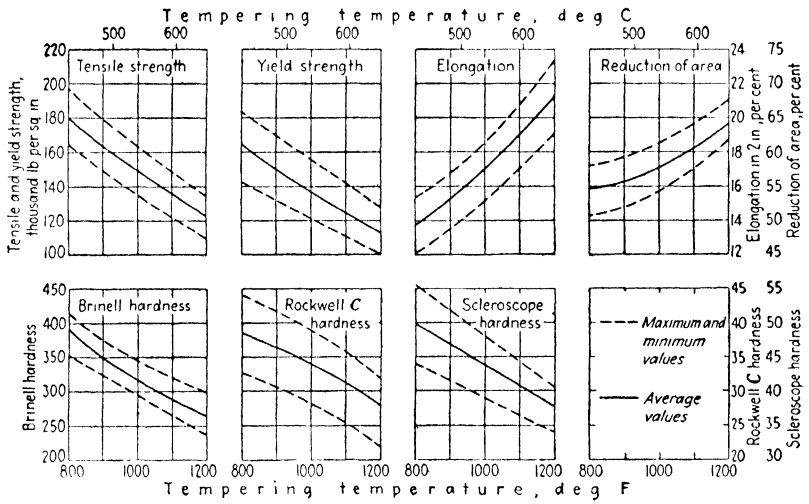


FIG. 117.—Mechanical properties of S.A.E. 6130 chromium-vanadium steel. (*Janitzky.*[217])

Janitzky[217] reported the results of a cooperative study of representative S.A.E. 6130 steels. The data are shown in Fig. 117. The values plotted were obtained by a study of the frequency curves obtained in a large number of tests. The maximum and minimum, shown by the dashed lines, and the average (value of greatest frequency), shown by the solid lines, for each tempering temperature were plotted as abscissas against the frequency of occurrence of each value as ordinates. These curves indicate accurately the range of values that may be

TABLE 102.—MECHANICAL PROPERTIES OF CHROMIUM-VANADIUM STEELS, AS ANNEALED AT 815°C. (1500°F.) OR AS WATER QUENCHED FROM DIFFERENT TEMPERATURES AND TEMPERED AT 565°C. (1050°F.)*

Composition, per cent				Quenching temperature		Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness	Charpy impact, ft-lb
C	Mn	Cr	V	°C.	°F.						
0.16	0.55	1.03	0.20	Annealed		68,000	48,000	37.0	71.9	129	44.8
				900	1650	114,700	103,100	22.5	68.0	231	
				925	1700	114,300	100,000	23.5	67.5	252	
				955	1750	122,200	112,500	20.5	67.0	255	
0.30	0.68	0.93	0.18	Annealed		70,000	53,000†	36.0	67.0	116	40.7
				845	1550	145,800	107,000	17.0	58.7	277	
				870	1600	152,800	115,000	17.0	55.5	297	
				900	1650	158,800	117,000	17.5	54.5	306	
0.58	0.68	0.73	0.18	Annealed		92,400	49,500†	28.0	43.5	163	28.3
				815	1500	162,000	125,000	16.0	49.5	293	
				845	1550	173,100	135,100	15.0	45.5	332	
				900	1650	180,800	140,000	13.5	37.5	351	
1.16	0.55	1.06	0.20	Annealed		102,500	63,200	26.5	48.0	194	2.2
				760	1400	103,100	59,800	22.0	45.0	212	
				790	1450	114,300	83,200	20.5	39.0	221	
				815	1500	133,000		17.0	31.0	262	
0.40	0.53	1.05	0.02	Annealed		88,300	46,300	26.0	45.8	170	14.6
				845	1550	119,800	94,500	22.0	66.5	259	
				870	1600	113,400	93,500	21.0	65.5	255	
				900	1650	124,800	106,700	20.0	63.5	255	
0.37	0.52	1.05	0.07	Annealed		80,300	51,000	33.0	59.9	143	20.1
				870	1600	132,400	121,100	20.0	59.0	282	
				900	1650	132,900	119,400	20.5	59.5	286	
				925	1700	134,800	121,400	20.0	58.0	289	
0.35	0.37	1.02	0.14	Annealed		78,800	49,000	32.0	59.3	144	29.8
				870	1600	144,800	135,500	16.5	57.8	302	
				900	1650	152,400	145,000	15.5	55.5	321	
				925	1700	158,800	147,500	15.0	52.7	338	
0.37	0.55	1.07	0.31	Annealed		83,800	52,300	31.5	61.0	159	31.3
				845	1550	119,500	110,500	21.5	64.0	263	
				870	1600	130,700	122,800	19.5	67.0	269	
				900	1650	132,700	128,300	19.5	58.5	286	
0.27	0.34	1.24	0.65	Annealed		81,500	51,300	30.0	70.3	158	5.7
				845	1550	165,900	147,900	15.0	55.0	332	
				870	1600	169,200	159,200	14.0	51.0	335	
				900	1650	160,000	144,000	11.0	55.4	344	
0.38	0.39	0.04	0.19	Annealed		75,150	50,000	32.0	55.7	143	6.6
				815	1500	88,850	62,850	32.0	64.5	185	
				845	1550	89,300	64,000	32.0	66.0	186	
				870	1600	104,050	74,500	24.0	62.0	207	
0.29	0.53	0.51	0.28	Annealed		72,800	49,500	34.0	62.2	136	27.6
				900	1650	113,800	95,900	23.5	62.5	239	
				925	1700	123,000	104,900	22.5	58.0	269	
				955	1750	130,100	115,300	21.5	63.0	286	
0.31	0.48	2.01	0.34	Annealed		73,800	51,400	34.0	73.2	143	43.1
				870	1600	131,900	121,600	21.0	65.0	286	
				900	1650	134,300	126,600	20.0	64.5	293	
				925	1700	149,100	138,200	20.5	63.0	321	

* Vanick.[115]
† Elastic limit.

expected of specimens whose compositions fall within the limits for steel of this specification.

TABLE 103.—EFFECT OF VANADIUM ON MECHANICAL PROPERTIES OF OIL-QUENCHED AND TEMPERED 0.35 PER CENT CARBON, 0.65 AND 1.20 PER CENT CHROMIUM STEELS*

Specimen No.	Quenching temperature		Tempering temperature		Cooled in	Tensile strength, lb /sq in.	Yield strength, lb /sq in.	Elongation in 2 in., per cent	Reduction of area, per cent	Izod impact, average of 3 tests, ft-lb.
	°C.	°F.	°C.	°F.						
10A	850	1560	600	1110	Air	111,600	93,200	26 0	64 0	39 0
	850	1560	650	1200	Air	112,300	94,100	25 0	64 0	46 0
	900	1650	600	1110	Air	130,800	106,800	22 0	54 0	12 0
	900	1650	650	1200	Air	117,300	95,400	24 0	58 0	19 0
	925	1700	500	930	Water	132,200	107,600	19 0	56 0	11 0
	925	1700	550	1020	Water	132,800	109,400	18 0	53 0	6.0
	925	1700	600	1110	Water	141,000	114,300	21 0	57 0	6 0
	925	1700	650	1200	Water	135,200	111,200	20 0†	58.0	7 0
	925	1700	700	1290	Water	131,400	86,000	23 0†	64 0	31 0
11	900	1650	600	1110	Air	129,800	101,300	16 0†	....	12 0
	900	1650	650	1200	Air	124,700	105,300	23 0	.	15 0
	925	1700	500	930	Water	129,300	102,600	22 0	57 0	17 0
	925	1700	550	1020	Water	133,800	108,400	21 0	54 0	9 0
	925	1700	600	1110	Water	131,700	108,900	22 0	55 0	13 0
	925	1700	650	1200	Water	131,900	107,600	23 0	56 0	15 0
	925	1700	700	1290	Water	114,000	91,600	25 0	63 0	23 0
13	850	1560	600	1110	Air	129,100	108,900	21 0	59.0	31 0
	850	1560	650	1200	Air	126,200	107,800	23 0	62 0	40 0
	900	1650	600	1110	Air	132,800	111,200	21 0	55 0	22.0
	900	1650	650	1200	Air	127,000	112,500	23 0	57 0	40 0
	925	1700	500	930	Water	150,700	130,900	17 0	53 0	22 0
	925	1700	550	1020	Water	142,000	122,800	18 0	54 0	21 0
	925	1700	600	1110	Water	144,900	125,800	20 0	57 0	20 0
	925	1700	650	1200	Water	136,200	120,100	19 0	57 0	23 0
	925	1700	700	1290	Water	112,900	103,600	22 0†	64 0	60 0
14	900	1650	600	1110	Air	144,000	121,400	21 0	...	16 0
	900	1650	650	1200	Air	123,000	107,200	23 0	.. .	47 0
	925	1700	500	930	Water	150,800	130,800	17 0	53 0	22 0
	925	1700	550	1020	Water	142,100	122,800	18 0	54 0	21 0
	925	1700	600	1110	Water	144,900	125,900	20 0	57 0	20 0
	925	1700	650	1200	Water	136,200	120,200	19 0	57 0	23·0
	925	1700	700	1290	Water	113,000	103,700	22 0†	64 0	60 0

* Abram.(411)

† Broke outside middle half.

Knerr(99) tested 6130 steel sheet in the heat-treated condition. His results, reproduced in Table 104, are the average values of

tests made on longitudinal and transverse specimens. It will be noted that at the strength comparable to that used for springs the 6130 steel is somewhat inferior to the S.A.E. 6150 grade, properties of which are discussed on page 325. A chart showing

TABLE 104.—MECHANICAL PROPERTIES* OF S.A.E. 6130 STEEL, OIL QUENCHED FROM 900°C. (1650°F.) AND TEMPERED AT DIFFERENT TEMPERATURES†

Size of sheet, in.	Composition, per cent					Tempering temperature		Tensile strength, lb /sq. in	Yield strength, lb /sq in.	Elongation, per cent		Reduction of area, per cent	Brinell hardness
	C	Mn	Si	Cr	V	°C.	°F.			In 2 in	In 4 in		
⅛	0 29	0 77	0 27	0.97	0 16	425	795	181,670	164,050	5 3	3 4	25 9	351
⅛	0 29	0 77	0 27	0 97	0 16	510	950	155,500	141,750	7 8	4 9	40 4	271
¼	0 29	0 77	0 27	0 97	0 16	425	795	186,450	162,700	8 0	4 8	38 2	364
¼	0 29	0 77	0 27	0 97	0 16	510	950	164,600	146,900	9 9	5 8	38 7	326

* Average values of tests made on longitudinal and transverse specimens
† Knerr.[99]

the effect of tempering on the properties of oil-quenched 6140 steel has been prepared by the Society of Automotive Engineers.

Typical *minimum* properties which may be expected after

TABLE 105.—TYPICAL MINIMUM PROPERTIES OF OIL-QUENCHED AND TEMPERED 6140 STEEL*

Tempering temperature		Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent
°C.	°F.				
425	800	180,000	160,000	13	42
540	1000	142,000	123,000	15	52
650	1200	114,000	93,000	19	59
705	1300	108,000	86,000	21	62

* Society of Automotive Engineers.[458]

tempering at various temperatures, taken from this chart, are as shown in Table 105. The actual tensile and yield strengths for steels of a composition falling in approximately the center of the analysis range are ordinarily 8000 to 10,000 lb. per sq. in.

TABLE 106.—TENSILE PROPERTIES, IMPACT, AND ENDURANCE LIMIT OF HEAT-TREATED 0.31 TO 0.60 PER CENT CARBON CHROMIUM-VANADIUM STEEL*

Composition, per cent					Quenching temperature		Quenched in	Tempering temperature		Tensile strength, lb./sq in	Yield strength, lb./sq. in	Elongation, per cent	Reduction of area, per cent	Brinell hardness	Izod impact, ft-lb.	Endurance limit, lb./sq. in.
C	Mn	Si	Cr	V	°C.	°F.		°C	°F							
0 40	0 64	0 31	0 93	0 20	900	1650	Oil	425	800	193 000	160 000	11 5	49 0	400	21 0	98,000
								525	975	164,500	152,500	16 5	54 5	360	42 0	79,000
								625	1155	145,500	130 000	18 0	58 0	305	57 0	62,000
0 41	0 67	0 13	0 93	0 16	900	1650	Air			126 000	91,000	22 5	62 5	235	36 0	66,000
							Oil	425	800	208,500	190,000	13 0	46 5	400	. . .	88,000
								525	975	183,500	167,500	14 0	46 5	350	. . .	74,000
								625	1155	154,500	142 500	17 0	52 0	300	. .	66,000
0 31	0.71	0 20	0 95	0 15	850	1560	Water	200	390	255,000	238 000†	6 5	26 0			
0 40	0 60	0 20	1 00	0 18	900	1650	Oil	425	800	226,000	200,000†	10 0	45 0			
0 42	0 75	0 15	1 04	0 15	870	1600	Oil	580	1080	175,000	167,000	11 0	48 0			
								630	1170	150,000	137,000	17 0	54 0			
								675	1250	125 000	110,000	24 0	57 0			
								750	1380	103,000	90,000	30 0	68 0			
0 50	0 92	0 07	1 02	0 20	830	1525	Oil	400	750	260,000	240,000†	8 0	24 0			
					900	1650	Oil	450	840	227,000	217,000	10 0	35 5			
								550	1020	201,000	186,000	13 0	45 5			
0 60	0 54	0 17	0 88	0 19	900	1650	Oil	400	750	273,000	249,000†	8 0	27 0			

* Gillett and Mack [137]

† Elastic limit.

higher for the lower tempering temperatures and 3000 to 5000 lb. per sq. in. higher for tempering temperatures of 650 and 705°C. (1200 and 1300°F.).

Gillett and Mack[137] determined the properties of a series of chromium-vanadium steels containing 0.31 to 0.60 per cent carbon. Their data are given in Table 106. These steels were hardened by quenching in oil and it will be noted that, on account of the high initial hardness, there was no appreciable secondary hardening effect. The ductility and impact strength were exceptionally high in the normalized condition.

The properties of S.A.E. 6140 steel in the form of wire have been studied by Rees;[230] some of his results are shown in Table 107. It will be seen that the cold-drawn wire regained a

TABLE 107.—EFFECT OF TEMPERING FOR 1 HR. ON MECHANICAL PROPERTIES OF *A* COLD-DRAWN AND *B* COLD-DRAWN AND OIL-QUENCHED CHROMIUM-VANADIUM WIRES*

Steel	Composition, per cent					Tempering temperature		Tensile strength, lb /sq in	Yield strength, lb /sq in	Proportional limit, lb /sq in.	Elongation in 2 in , per cent	Brinell hardness
	C	Mn	Si	Cr	V	°C	°F					
A†	0 42	0 56	0 24	1 11	0 20			239,900	201,600	100,800	2 5	418
						100	210	244,800	212,800	103,100	1 0	415
						200	390	249,300	229,200	165,800	3 0	428
						250	480	255,800	247,800	192,600	2 0	457
						300	570	248,200	242,600	197,100	4 0	448
						400	750	229,800	227,600	179,200	4 0	444
						450	840	218,000	213,500	174,800	5 5	426
						500	930	202,000	200,700	163,500	6 0	408
						550	1020	192,900	192,600	154,600	6 0	392
						600	1110	120,900	120,100	91,800	13 0	268
B‡	0 43	0 66	0 22	0 93	0 23	525	975	218,700	201,400	159,000	6 0	
						300	570	217,600	203,200	163,500	6 0	
						350	660	214,800	201,600	161,200	5 5	
						400	750	213,500	200,500	168,000	6 0	
						450	840	178,600	170,000	147,800	7 0	

* Rees [230]

† Steel *A* was cold drawn from 0 375 × 0.212-in. rod to 0 25 × 0.06-in. wire

‡ Steel *B*, in the form of 0 25 × 0 06-in wire, was oil quenched from 900°C (1650°F.) and tempered 15 sec. at 525°C. (975°F.), then retempered for 1 hr at temperatures shown (300 to 450°C).

high proportional limit at 250 to 300°C. (480 to 570°F.) and that higher tempering temperatures—up to 550°C. (1020°F.)—reduced the strength gradually. The cold-drawn and heat-

treated material retained a high degree of strength after 1 hr. at 400°C. (750°F.).

129. Properties of Chromium-vanadium Spring Steels.—The chromium-vanadium steels with from 0.45 to 0.60 per cent carbon have been widely used in gears and springs, and a number of investigators have studied the properties with particular reference to fatigue and decarburization. McAdam[127] carried out tensile, torsion, and fatigue tests on a steel with 0.55 per cent carbon, 0.99 per cent chromium, and 0.19 per cent vanadium as shown in Table 108. The steel was tested after annealing and after water quenching so that the results are of little practical interest, although the steel showed good properties in spite of the drastic heat treatment. Data on oil-quenched steel in this carbon range were also reported by Vanick[115] (Table 102), Gillett and Mack[137,154] (Table 106), and Bullens[195] (Table 101). It will be seen that, although no secondary hardness is apparent, the steels require high tempering temperatures for softening. In the range of 200,000 lb. per sq. in. tensile strength the ductility and impact strength are particularly good.

A comprehensive series of tests on chromium-vanadium spring steel has been carried out by Hankins and associates.[181,244,324,450] The tensile, torsion, and fatigue properties of this steel as oil hardened and tempered are shown in Table 109. The endurance-limit values in Table 110, illustrating the effect of surface condition, include those of other investigators as given by Hankins and Becker.[324] The loss in endurance limit reported by Hankins and Ford[244] (Table 110) due to heat-treated surface amounted to 25 per cent, as compared with 41 per cent for silicon-manganese spring steel. Tests on full-size springs indicated that safe ranges of stress were limited to 45,000 ± lb. per sq. in. Further work[324] demonstrated that the full endurance limit might be attained by completely avoiding surface decarburization. Heating in a sodium cyanide bath at 850°C. (1560°F.) or heat treatment in which the specimens were covered with graphite was effective. Hankins and Mills[450] showed that repeated-impact endurance limits corresponded to those of cyclic loading.

Johnson[426] tested chromium-vanadium steel as received in the form of helical springs. The steel contained 0.52 per cent carbon, 0.66 per cent manganese, 0.88 per cent chromium, and

TABLE 108.—TENSILE, TORSIONAL, AND FATIGUE PROPERTIES OF 6150 STEEL CONTAINING 0.55 PER CENT CARBON, 0.99 PER CENT CHROMIUM, AND 0.19 PER CENT VANADIUM*

Specimen No.	Quenching temperature		Cooled in	Tempering temperature		Tension test				Charpy impact, ft-lb.	Torsional test				Endurance limit for 10^7 cycles, lb /sq. in.
	°C.	°F.		°C.	°F.	Tensile strength, lb./sq. in	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent		Nominal torsional strength, lb./sq. in	Proportional limit, lb /sq. in	Angle of twist per linear inch at proportional limit, deg.	Angle of twist per linear inch at break stress, deg.	
1	900	1650	Furnace			101,800	51,500	25 5	48 5	16 0	77,000	33,800	28	128	44,500
2	900	1650	Water	480	900	201,000	165,000	13 3	53 5	9 8	124,100	103,800	80	29	94,500
3	900	1650	Water	595	1100	164,400	130,500	15 5	50 5	14 2	110,500	106,300	87	97	92,000

* McAdam.(127)

TABLE 109.—TENSILE, TORSIONAL, AND FATIGUE PROPERTIES OF SPRING STEEL NORMALIZED OR OIL QUENCHED FROM 850°C. (1560°F.) AND TEMPERED AS SHOWN, CONTAINING 0.54 PER CENT CARBON, 0.68 PER CENT MANGANESE, 0.29 PER CENT SILICON, 1.16 PER CENT CHROMIUM, AND 0.27 PER CENT VANADIUM*

Tempering temperature		Tensile tests					Brinell hardness	Izod impact, ft-lb.	Torsional tests				Estimated fatigue limit, lb./sq. in.
°C.	°F.	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 8 in., per cent	Reduction of area, per cent	Modulus of elasticity, million lb./sq. in.			Proportional limit, lb./sq. in.	Ultimate modulus of rupture, lb./sq. in.	Modulus of rigidity, million lb./sq. in.	Total angle of twist in 4 in., deg.	
Normalized		156,000	103,000†	10 6	47 0	30 3	300						
400	750	250,100	236,850	5 6	12.0	30 3	500	9.0	131,200	205,000	11.75	122.5	105,200 ±
475	885	235,900	231,850	4 9	19 0	30 1	485	13 0	114,300	175,000	11 60	265.0	97,500 ±
550	1020	189,400	183,000	7 3	32 0	30 6	410	20 1	98,600	153,200	11 65	589.0	97,500 ±
600	1110	178,050	169,200	7 4	31 0	30 7	386	30 5	89,600	148,300	11 80	503.5	95,200 ±

* Hankins, Hanson, and Ford.(181)

† Reported as proportional limit.

0.21 per cent vanadium and was quenched from 870°C. (1600°F.) in oil at 55°C. (130°F.) and tempered at 430°C. (810°F.). The wire was 0.526 in. in diameter and was coiled into an eight-coil spring of 3.25 in. outside diameter, 7.75 in. open height, and

TABLE 110.—EFFECT OF SURFACE ON ENDURANCE LIMIT OF 6150 CHROMIUM-VANADIUM SPRING STEEL*

Investigator	Endurance limit, lb./sq. in.		
	Not polished	Polished	Ratio
Hankins and Ford[244]	71,600 ±	95,200 ±	0.75
Lea and Heywood[203]	33,600 ±	62,700 ±	0.54
Swan, Sutton, and Douglas[347]	21,300 to 85,200	32,700 to 130,000	0 65

* Hankins and Becker.[324]

4.45 in. closed height. Tensile, torsion, rotating-beam, and torsion-fatigue tests were made on straight bars. The results of the tests are given in Table 111. The notch in the rotating-beam test was cut with a 24-pitch threading tool to a depth of 0.025 in. with a 0.003 in. radius at the bottom.

TABLE 111.—TENSILE, TORSION, AND FATIGUE PROPERTIES OF 6150 CHROMIUM-VANADIUM SPRING STEEL*

Property	Tensile tests	Torsion tests	Endurance limit
Tensile strength, lb. per sq. in.	237,000		
Yield strength, lb. per sq. in	229,000	141,000	
Elongation in 2 in., per cent	11 0		
Brinell hardness	477 to 488		
Modulus of rupture		183,000	
Rotating-beam fatigue			104,000
Rotating-beam fatigue with 60-deg. V notch			28,000
Torsion fatigue (0 to maximum)			128,000
Torsion fatigue (reversed)			75,000
Complete spring (1,000,000 cycles; 0 to maximum)			82,000

* Johnson.[426]

Moore[188] and McAdam[223] have used chromium-vanadium steel for studies of the effects of surface irregularities and corro-

sion on endurance limit; they found the steel to be typical of other low-alloy grades in its resistance to corrosion fatigue.

130. Effect of Mass.—While vanadium refines the grain and has a secondary hardening influence that mitigates to some extent its shallow-hardening tendencies, it is ordinarily used with more powerful deep-hardening alloys in heavy sections. Hohage and Grützner[141] quenched from 900°C. (1650°F.) in oil and tempered at 500°C. (930°F.) 250-mm. (10-in.) diameter bars of a steel containing 0.38 per cent carbon, 0.36 per cent manganese, 0.20 per cent silicon, 1.06 per cent chromium, and 0.47 per cent vanadium. They obtained the following results:

Location of specimen	Tensile strength, lb./sq in	Yield strength, lb./sq. in.	Elongation, per cent ($l = 5d$)	Reduction of area, per cent	Charpy impact, m-kg. per sq. cm.
Outside	95,400	61,500	14 8	50 0	11 9
Center	91,600	57,800	15 8	44 0	6 7

It will be seen that mass has made itself evident primarily in the impact strength. Similar results were found by Kallen and Schrader[286] and by Houdremont, Bennek, and Schrader.[366] Tensile tests on heavy sections were reported by Bullens,[195] as shown in Table 101 (page 318). The effect of mass in S.A.E. 6130 steel in small sections was determined by Dawe.[103] Results are given in Table 112. At low tempering temperatures the strength was lower in the 2-in. square section than in the smaller ones, but after tempering at 650°C. (1200°F.) there was no loss of strength. It will be noted that the S.A.E. specifications for manganese in these steels have been revised upward to 0.60 to 0.90 per cent to obtain greater depth hardening. In sections of over 1½ in. in diameter, the manganese should be on the high side of the range.

131. Temper Brittleness.—Several investigators have tested chromium-vanadium steels for temper brittleness and have found that vanadium has little influence. Typical results are shown in Table 113 taken from the work of Greaves and Jones.[155] The secondary hardening, which may be a true precipitation hardening, does not appear to be related to temper brittleness and is not associated with abnormal decrease of shock resistance.

TABLE 112.—EFFECT OF SECTION ON TENSILE PROPERTIES OF 6130 STEEL CONTAINING 0.32 PER CENT CARBON, 0.75 PER CENT MANGANESE, 1.03 PER CENT CHROMIUM, AND 0.16 PER CENT VANADIUM, WATER QUENCHED FROM 870°C. (1600°F.)*

Diameter of section, in.	Tempering temperature		Tensile strength, lb./sq. in.	Yield strength,† lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent
	°C.	°F.				
⅞	540	1000	157,770	148,900	19 4	54 6
⅞	595	1100	140,030	127,570	22 7	57 5
⅞	650	1200	131,980	119,000	23 6	60 6
1	540	1000	158,770	147,750	19 8	54 8
1	595	1100	139,300	127,100	23 4	58 3
1	650	1200	116,500	101,950	26 9	64 8
1½	540	1000	140,200	129,850	20 9	57 6
1½	595	1100	134,900	117,800	23 5	61 0
1½	650	1200	118,500	102,400	26 5	67 0
2‡	540	1000	119,500	104,400	24 2	61 5
2‡	595	1100	127,800	112,800	24 3	59 0
2‡	650	1200	123,800	107,500	23 4	59 0

* Dawe.[103]
† Reported as elastic limit
‡ Square bars.

TABLE 113.—TEMPER BRITTLENESS OF CHROMIUM AND CHROMIUM-VANADIUM STEELS*

Steel No.	Composition, per cent					Oil quenched from			
						900°C. (1650°F.)		1000°C. (1830°F.)	
						Izod impact value, ft-lb., after tempering at 650°C. (1200°F.) and cooling			
	C	Mn	Si	Cr	V	In water	Slowly†	In water	Slowly†
36	0.37	0.22	0.13	0.75	.	53	49	46	40
37	0.30	0.19	0.07	0.65	0.39	49	48	16	13
38	0.36	0.19	0.12	0.63	0.63	37	33	15	10
6	0.38	0.22	0.15	1.43	. .	66	62	59	41
39	0.36	0.21	0.12	1.20	0.38	58	38	19	9
40	0.34	0.21	0.11	1.20	0.68	61	41	19	8

* Greaves and Jones.[155]
† At the rate of 0.3°C. (0.5°F.) per min.

132. Effect of Temperature on Impact and Torsional Properties.—Sergeson[375] tested the impact strength of heat-treated chromium-vanadium spring steel above and below room temperature. Notched specimens had gradually decreasing resistance to impact as the temperature was lowered from 225 to −25°C. (435 to −15°F.), but unnotched specimens showed very little drop. Substantial impact strength was retained at the lowest temperature used, −45°C. (−50°F.). Tests by Egan, Crafts, and Kinzel[385] on normalized chromium-vanadium steels with 0.20 to 0.50 per cent carbon also indicated retention of fairly good impact strength down to −50°C. (−60°F.) and gradual falling off at lower temperatures. Chromium-vanadium steels therefore apparently have adequate impact strength for most applications within the range of atmospheric subzero temperatures.

On account of the wide use of chromium-vanadium steel in coiled springs, its variations in torsional characteristics have been studied. Zimmerli, Wood, and Wilson[308] determined the modulus of rigidity at various temperatures on a heat-treated steel containing 0.47 per cent carbon, 0.56 per cent manganese, 1.06 per cent chromium, and 0.17 per cent vanadium. Their results showed the modulus of rigidity to follow an almost straight line from 11,450,000 lb. per sq. in. at −75°C. (−105°F.) to 9,950,000 lb. per sq. in. at 315°C. (600°F.). Further work by the same investigators[409] showed that at a stress of 65,000 lb. per sq. in. in helical springs of 0.53 per cent carbon, 0.63 per cent manganese, 1.03 per cent chromium, and 0.17 per cent vanadium, loaded for 72 hr., the reduction of load sustained was low up to 205°C. (400°F.), but above this temperature it increased rapidly. Smaller loads could be borne at higher temperatures. Brombacher and Melton[266] made tests of modulus of rigidity on chromium-vanadium wire, with the results shown in Table 114. Rees[230] made tests on heat-treated and on cold-drawn and tempered chromium-vanadium steel wire to determine loss of tension in bending and tensile loading under a stress of 112,000 lb. per sq. in. The temperatures at which loss of tension in bending amounted to 5 per cent and which in direct loading caused a permanent set of 0.03 per cent are shown in Table 115. He concluded that cold-drawn and tempered chromium-vanadium steel was suitable for springs operating at slightly elevated temperatures.

133. Short-time Elevated-temperature Tests and Creep Tests. Short-time tensile tests at elevated temperatures were made on chromium-vanadium steels by French[107] and Hatfield.[213] The steels used and the heat treatments were as shown in the table at the top of page 333.

TABLE 114.—MODULUS OF RIGIDITY OF CHROMIUM-VANADIUM STEELS*

Steel No.	Composition, per cent				Tempering temperature		Temperature coefficient	Modulus of rigidity, million lb./sq. in.	Stress range, thousand lb./sq. in.	Increase of rigidity in indicated range, per cent
	C	Mn	Cr	V	°C.	°F.				
13	0.55	0.65	0.98	0.19	As received		−0.00029	12.6	30 to 130	0.40
					100	210	−0.00032	11.9	30 to 130	0.44
					200	390	−0.00034	12.0	30 to 130	0.44
					300	570	−0.00031	12.0	30 to 130	0.20
					400	750	−0.00027	12.1	30 to 130	0.20
					500	930	−0.00026	12.1	30 to 130	0.20
					625	1155	−0.00029	12.0	30 to 130	0.20
18	0.50	0.64	0.97	0.18	As received		−0.00030	11.4	20 to 100	0
					100	210	−0.00035		20 to 100	−0.34

* Brombacher and Melton [266]

TABLE 115.—TEMPERATURES AT WHICH 5 PER CENT LOSS OF TENSION IN BENDING AND 0.03 PER CENT SET IN TENSILE LOADING OCCURRED IN CARBON AND CHROMIUM-VANADIUM SPRING STEELS*

Steel and treatment	Temperatures for	
	Bending	Direct loading
Carbon steel, oil quenched from 900°C. (1650°F.) and tempered at 400°C. (750°F.)	150°C. (300°F.)	
Chromium-vanadium steel (same treatment as above)	< 200°C. (390°F.)	150°C. (300°F.)
Carbon steel, cold drawn and reheated to 300°C. (570°F.)	160°C. (320°F.)	160°C. (320°F.)
Chromium-vanadium steel, cold drawn and reheated to 400°C. (750°F.)	300°C. (570°F.)	250°C. (480°F.)

* Rees.[230]

The rate of loading used by French was 0.05 in. per min., and the strain was measured by extensometers outside the furnace.

Investigator	Composition, per cent					Quenching temperature		Cooled in	Tempering temperature	
	C	Mn	Si	Cr	V	°C.	°F.		°C.	°F.
French[107]. . . .	0 37	0 74	0 21	1 04	0 17	850	1560	Air		
Hatfield[213].	0 43	0 59	0 22	1 14	0 18	850	1560	Oil	640	1185

Proportional limit was determined graphically. Hatfield's loading rate was 0.25 in. per min.

TABLE 116.—SHORT-TIME ELEVATED-TEMPERATURE PROPERTIES OF CHROMIUM-VANADIUM STEELS

Investigator	Temperature of test		Tensile strength, lb./sq in	Yield strength, lb /sq. in.	Proportional limit, lb /sq in.	Elongation in 2 in , per cent	Reduction of area, per cent
	°C	°F					
French[107]. . . .	20	70	144,300		88,000	19 5	42 5
	95	200	141,800		74,650	17 7	48 8
	155	310	141,350		77,500	20 0	55 7
	240	465	135,400		80,500	20.0	56 0
	295	560	142,250		74,500	19.0	45 8
	405	765	111,600		50,750	25 0	69 5
	465	865	99,250		28,000	23 0	57 7
	550	1020	83,300		17,000	20 5	58 0
Hatfield[213]. . . .	15	60	136,600	124,600		21 6	61 5
	100	210	140,200	128,900		20 0	63 0
	200	390	133,400	119,000		15 6	61 5
	300	570	124,800	110,200		20 0	59 0
	400	750	123,900	104,400		15 6	61 5
	500	930	73,000	60,500		26 4	74 4
	600	1110	55,600			30 4	87 0
	700	1290	26,000			52 0	92 0
	800	1470	15,000			68 0	95 0
	900	1650	10,500			81 5	96 0
	1000	1830	6,900			73 0	97 0

Several determinations of the creep strength of chromium-vanadium steel are collected in Table 117. Although it is difficult from these data to estimate the creep strength quantitatively, it is apparent that chromium-vanadium steel has appreciable high-

TABLE 117.—CREEP STRENGTH OF CHROMIUM-VANADIUM STEELS

Investigator	Composition, per cent				Treatment	Creep strength, lb. per sq in., at			
	C	Cr	V	Mn		425°C 800°F	480°C. 900°F.	540°C. 1000°F	650°C. 1200°F
For a creep rate of 1 per cent in 100,000 hr.									
Norton[253]	0.40	0.79	0.57		Annealed	...	9,000	5,000	
Spooner and Foley[346]	0.32	1.04	0.18	0.70	Oil quenched from 870°C. (1600°F) and tempered at 560°C. (1045°F)		10,000	4,900	
White, Clark, and Wilson[443]	0.40	1.01	0.17	0.75	Oil quenched and tempered at 650°C (1200°F)			1,400	
For a creep rate of 0.1 per cent in 1000 hr									
French, Kahlbaum, and Peterson[277]	0.40	2.26	0.20	0.57	*A**	10,000		3,000	500
					B†	6,000		1,500	300
For a creep rate of 1 per cent in 1000 hr.									
French, Kahlbaum, and Peterson[277]	0.40	2.26	0.20	0.57	*A**	15,500		5,000	1,000
					B†	13,000		5,500	1,500

* Treatment *A* heated to 855°C. (1575°F.), cooled in silocel, and reheated to 745°C. (1375°F.).

† Treatment *B* heated to 855°C. (1575°F.), cooled in air, and reheated to 705°C. (1300°F.).

temperature strength up to about 500°C. (930°F.). Edert[104] conducted a series of accelerated creep and high-temperature ductility tests and recommended a 2 per cent chromium-vanadium steel for moving parts requiring exactness of fit and freedom from oxidation at temperatures up to 500°C. (930°F.). Bailey, Dickenson, Inglis, and Pearson[311] stated that 1 per cent chromium-vanadium steel had been found satisfactory for service at temperatures up to 400°C. (750°F.) but that its strength fell off

rapidly at higher temperatures. The impact strength has been shown by Edert[104] and by Greaves and Jones[156] to be little affected by temperatures up to 500°C. (930°F.).

134. Fabrication.—Chromium-vanadium steel may be sheared, punched, and stamped without extra precautions, as the ductility of the rolled material is excellent and the fine grain inhibits cracking. In general, the steel has a high yield strength so that more power is required in forming operations than would normally be required in steel of similar tensile strength. Chromium-vanadium steels may be readily welded by the metallic-arc or oyxacetylene process. Formerly chromium-vanadium sheet and tubing were used for airplane construction, but the more rapid softening on tempering and lack of air hardening have made them somewhat inferior to chromium-molybdenum steel in this field. For applications in which it can be used in the normalized condition, excellent physical properties make chromium-vanadium steel very suitable. The steel also makes a good filler rod.

As is well known, tests of machinability are difficult to evaluate and comparative estimates are often confusing. Chromium-vanadium steel is no exception in this regard. For example, French and Digges[178] found that a chromium-vanadium steel was the only outstandingly bad steel of the series tested, whereas Digges[317] in later work found it to be the best in the intermediate strength range under different test conditions. Aside from hardness, grain size seems to be the most important factor in machinability, and McQuaid[429] has pointed out that improved machinability of chromium-vanadium steel can be gained by heating to temperatures over 925°C. (1700°F.) to enlarge the grain size. Subsequent heat treatment at lower temperatures restores the small grain size desired in the finished article. Boston and Landis[237] studied the effect of heat treatment of S.A.E. 6140 steel on machinability and came to the conclusion that the best condition was when the steel had been completely spheroidized by a subcritical anneal. Although it cannot be claimed that chromium-vanadium steel at its best is any better than other steels of equal grain size, the flexibility of grain-size control permits ready machining of steel that is subsequently treated to produce a very tough structure.

135. Chromium-vanadium Steel Castings.—Vanadium is used in steel castings primarily to obtain fine grain and soundness.

Typical properties for chromium-vanadium steel castings are shown in Table 118. According to Strauss[402] the principal advantage of the addition of vanadium lies in the increased impact strength. The castings are usually normalized and tempered. In addition to heavy castings and parts subject to abrasion and dynamic loading, the steel is used for rolling-mill rolls, valves, and fittings where high-temperature strength is required.

136. Special Chromium-vanadium Steels.—Steels for special purposes such as steels used for nitriding and in chemical industries are discussed in Chapter XI.

Molybdenum may be added to various chromium-vanadium steels if increased freedom from mass effect and temper brittleness is desired. Nickel may be added for high-temperature strength and deep hardening. A water-hardening manganese-chromium-vanadium steel suitable for crankshafts has been recommended by Chandler and Dawe.[382] The analysis recommended is within the following limits: carbon 0.27 to 0.45 per cent, manganese 1.05 to 1.30 per cent, chromium 0.30 to 0.40 per cent, and vanadium 0.08 to 0.11 per cent. Tensile and impact properties of such a steel with carbon ranging from 0.09 to 0.13 per cent are given in Table 119. A similar steel low in carbon has been found to have good carburizing properties and little tendency to distortion. Some use has been made of a nickel-chromium-vanadium steel, the properties of which are shown in Table 120. Vanadium may be added with advantage to practically all types of steel, and it is unnecessary to enumerate them all or give their properties in this discussion.*

137. Uses.—Low-carbon chromium-vanadium steel finds wide application in carburized parts such as differential gears, shafts, piston pins, and steering worms where ease of machining, rate of carburizing, simple heat treatment, lack of distortion, toughness, and wear resistance are utilized. In the medium-carbon grades the steel is used for bolts, washers, crankshafts, connecting rods, axles, drive shafts, small tools, and forgings in automobiles, aircraft, and general machinery, as well as in boiler and pressure-vessel construction for chemical and oil equipment. The higher carbon grades are used chiefly for gears and springs. Gears are tough and wear resistant and on account of the fine grain and

* A monograph on iron-vanadium alloys is in preparation.

TABLE 118.—TENSILE PROPERTIES OF CHROMIUM-VANADIUM CASTINGS

Investigator	Specimen	Composition, per cent					Quenching temperature		Cooled in	Tempering temperature		Tensile strength, lb./sq. in.	Yield strength, lb./sq in	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness	Izod impact, ft-lb.
		C	Mn	Si	Cr	V	°C	°F.		°C.	°F.						
Herzog, according to Lorig and Williams[368]	1A	0 42	1 45	0 80	0 38	0 16	900	1650	Air	620	1150	116,000	74,000	18 5	42 5		
									Air	785	1445	108,000	62,000	20 0	47 2		
									Oil	620	1150	115,000	74,000	21 0	41 0		
									Oil	785	1445	105 000	73,000	25 5	48 9		
	2A	0 32	1 14	0 68	0 47	0 20	As cast					122,000	103 000	2 0	3 1		
							900	1650	Air	695	1285	97 000	71 000	28 0	60 3		
	3A	0 25	1 20	0 47	0 52	0 17	As cast					109,000	78,000	5 0	4 0		
							900	1650	Air	650	1200	107,000	85,000	23 0	50 0		
Gillett and Gregg[388]	4	0 32	1 51	0 29	0 47	0 16	*			705	1300	89 250	70.250	26 5	50 0	160	56 0
Strauss[402]	5	0 30	0 80	0 40	1 00	0 10	†					94 300	64 850	27 5	57 1		59.3
	6	0 24	1 32	0 40	0 61	0 10	†					94,000	70,000	29 0	60 0	.	61 0
	7	0 30	1 51	0 46	0 83	0 10	†					107,500	82,000	27 0	58 0	.	50.0
	8	0 44	1 48	0 47	0 61	0 10	†		.			119,250	76,600	25 0	56.2	.	34 5

* Double normalized at 925 and 830°C. (1700 and 1525°F.)

† Double normalized and tempered; temperatures of treatment not given.

shallow-hardening properties tend to distort little on heat treatment. Chromium-vanadium steel is unexcelled for springs and is used in laminated and helical springs for automobile and railroad cars as well as for valve springs. In gear steels, the use of chromium-vanadium steel appears to be growing, and further development in this application may be expected, although it is

TABLE 119.—MECHANICAL PROPERTIES OF MANGANESE-CHROMIUM-VANADIUM STEELS*

Composition, per cent				Tempering temperature		Tensile strength, lb /sq. in.	Yield strength, lb /sq in.	Elongation in 2 in., per cent	Reduction of area, per cent	Izod impact, ft-lb.
C	Mn	Cr	V	°C.	°F.					
1-in. diameter bar, normalized										
0 09	1 01	0 32	0 11	...	....	58,100	44,700	41 0	80 6	108
0 13	0 97	0 37	0 10	...	....	72,100	57,800	36 5	74 7	104
0 20	1 38	0 35	0 09	..	....	91,000	68,200	31 5	68 3	98
0 28	1 10	0 35	0 10	..	....	94,800	71,400	30 0	67 0	86
0 28	1 38	0 38	0 11	..	...	102,900	71,800	28 0	64 0	93
0 41	1 19	0 34	0 11	..	..	111,300	76,200	26 0	62 1	49
0 53	0 96	0 44	0 10	595	1100	121,200	77,800	23 0	52 8	
0 63	1 05	0 37	0 11	595	1100	131,000	74,000	20 0	48 8	
0 73	1.04	0 42	0 10	595	1100	140,600	75,500	18 0	39 8	
1-in. diameter bar, water quenched and tempered										
0 14	1 03	0 73	0 11	175	350	125,400	75,400	32 0	34 7	43
0 14	1 02	1 15	0 11	175	350	142,800	99,200	18 5	41 3	30
0 18	1 05	0 75	0 11	175	350	151,400	99,700	15 5	31 8	18
0 18	1 17	1 18	0 11	175	350	163,000	98,200	12 5	33 4	23
0 13	1 89	1 22	0 10	175	350	154,300	119,400	16 0	47 8	42
0 16	1 78	1 18	0 12	175	350	177,500	121,000	12 0	43 4	27
0 31†	1 66	0 65	0 17	480	900	166,300	157,800	17 0	61 8	70
0 32	1 09	0 94	0 10	480	900	173,700	166,400	16 0	56 5	46
0 32	1 86	0 38	0 11	480	900	166,900	162,200	16 0	57 3	57
0 34	1 09	0 65	0 10	480	900	164,500	153,000	15 5	53 3	50
0 42	1 09	0 65	0 09	480	900	183,500	174,600	15 0	50.6	32
½-in. section, oil quenched and tempered										
0.53	0 96	0 44	0 10	480	900	183,100	167,300	15.0	51 0	27
0.63	1 04	0.37	0 11	480	900	186,200	172,600	15 0	46 2	21
0 73	1 04	0 42	0 10	480	900	194,800	179,800	14 0	44 8	17

* Chandler and Dawe.[382]

† Contains 0.73 per cent silicon.

probable that some change of the chromium-vanadium analysis may improve the steel still more. Another growing use is in forged machine parts that are normalized after trimming and straightening, on account of the high ductility of chromium-vanadium steel after air cooling.

TABLE 120.—MECHANICAL PROPERTIES OF THE CORE OF STEEL CONTAINING 0.10 TO 0.20 PER CENT CARBON, 0.30 TO 0.60 PER CENT MANGANESE, 0.40 TO 0.60 PER CENT CHROMIUM, 0.40 TO 0.60 PER CENT NICKEL, AND 0.15 PER CENT VANADIUM, CARBURIZED 8 HR. AT 900°C. (1650°F.)*

Size of section carburized, in.	Oil quenched from		Tempered at		Tensile strength, lb./sq in.	Yield strength, lb /sq in.	Elongation in 2 in , per cent	Reduction of area, per cent	Brinell hardness	Izod impact, ft-lb.
	°C.	°F.	°C.	°F.						
5 × 1	900	1650	150	300	121,000	97,000	18 5	53 0	277	54 to 58
	775	1425	150	300	95,500	56,000	22 5	47 5	192	27 to 31
	800	1475	150	300	99,000	62,500	23 0	50 5	192	26 to 30
	830	1525	150	300	104,000	66,000	23 0	52 0	196	24 to 27
2 × 0 505	900	1650	150	300	138,000	116,000	18 5	58 0	302	60 to 64
	775	1425	150	300	100,000	63,000	20 0	40 0	207	43 to 47
	800	1475	150	300	103,000	70,000	21 0	48 0	212	45 to 50
	830	1525	150	300	111,000	85,000	23 0	59 0	228	95 to 99

* Republic Steel Corporation, 1935 catalogue.

C. LOW-CHROMIUM ENGINEERING STEELS CONTAINING TUNGSTEN OR OTHER ALLOYS

Early work by Guillet[39] indicated that the influence of tungsten on the mechanical properties of complex low-alloy steels was relatively small in comparison with nickel, chromium, and vanadium, and his conclusions have been substantiated by later experience. Although low chromium-tungsten steels have not found much application in the past for engineering purposes, they have been used to some extent where strength at moderately elevated temperatures is desired, and for armor plate, tools, and magnets, which are discussed in later chapters. Tungsten has been used to some extent as a substitute for molybdenum in reducing susceptibility to temper brittleness, and it is to be anticipated that the special characteristics of tungsten may lead to many other specialized applications.

138. Manufacture and Heat Treatment.—Chromium-tungsten steels require the usual care in melting and refining that characterizes most high-quality alloy steels. As tungsten oxide is reduced by iron without undue difficulty, the addition, usually ferrotungsten or tungsten powder, may be made early in the heat to insure uniform distribution. Small amounts of tungsten have little effect on scaling, although Pfeil[254] has shown that tungsten tends to be concentrated in the inner scale layer.

The effect of tungsten in carbon steels is to raise slightly the critical temperature on heating. Jones,[162] in a study of chromium-nickel-tungsten steels, found that each 1 per cent tungsten raised Ac_1 by 8°C. (14°F.) and had even less effect in the more complex alloy steels. The critical temperatures on cooling were lowered somewhat by tungsten when nickel and chromium were present. On tempering, the plain tungsten steels softened less readily than carbon steel, but in the presence of chromium the effect was largely masked.

Tungsten alone has a mild tendency to lower the critical temperatures and to decrease the effect of mass, but its influence is relatively small compared with that of the other common alloys. Döpfer and Wiester[416] have shown, in transformation at constant temperature, that tungsten steel has a relatively short interval before transformation starts and that in the range of 300 to 500°C. (570 to 930°F.) the rate of transformation is exceedingly high. In high-carbon low-tungsten steels chromium is usually added to increase hardening capacity. Zieler[263] indicated that this was due to the formation of tungsten carbide at temperatures in the heat-treating range. Steels of the following composition were held 4 hr. at temperature and quenched in water from 830°C. (1525°F.):

Composition, per cent				
C	Mn	Si	Cr	W
0.75	0 37	0.32	....	5.77
0.75	0.35	0.36	0.35	5.46

It will be noted from Fig. 118 that the small addition of chromium very materially reduced the range of temperature and the amount of the softening effect.

139. Mechanical Properties of Chromium-tungsten Steels.—Relatively few data have been published on the mechanical properties of chromium-tungsten steel. As shown by Gregg,[420] Parkin[146] studied the properties of a steel containing 0.11 to 1.46 per cent carbon, 0.75 per cent chromium, and 6.0 per cent tungsten. In the annealed condition the properties were equivalent to those of similar plain tungsten steels studied by Guillet.[32] After normalizing, the properties were about what would be

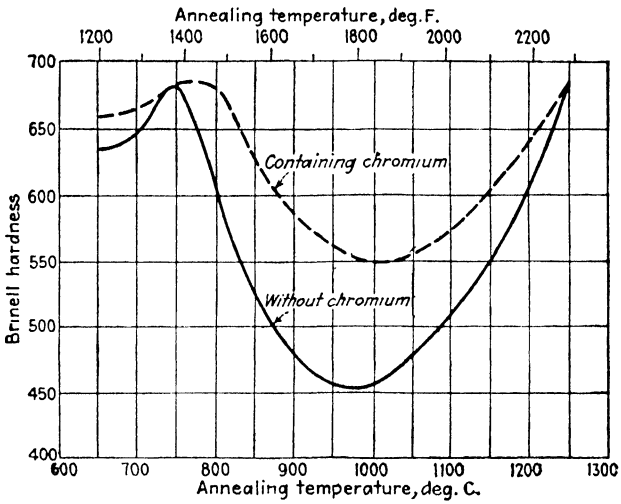


FIG. 118.—Relation between Brinell hardness and annealing temperature. The steels were annealed 4 hr at indicated temperatures and quenched in water from 830°C. (1525°F.); they contained *A* 0.75 per cent carbon, 0.37 per cent manganese, 0.32 per cent silicon, 5.77 per cent tungsten, and no chromium and *B* 0.75 per cent carbon, 0.35 per cent manganese, 0.36 per cent silicon, 5.46 per cent tungsten, and 0.35 per cent chromium. (*Zieler.*[263])

expected of steel with 1 to 1.5 per cent chromium. In the quenched and tempered condition, the ductility was too low to allow an estimate of the value of these steels for engineering uses.

Jones[162] found that heat-treated chromium-nickel steels were benefited by increase of tungsten to 1.2 per cent. As shown in Fig. 119, the tensile and impact values were very good, but equivalent properties could be gained by the use of 0.5 per cent chromium instead of tungsten. In the higher chromium chromium-nickel steel, 0.70 per cent tungsten had no beneficial effect.

Kinzel,[221] in the course of a study of the effect of chromium on silicon-manganese structural steel, tested a steel with 0.24 per cent carbon, 1.06 per cent manganese, 1.25 per cent silicon, 0.96 per cent chromium, and 2.33 per cent tungsten. The steel had the following properties:

Treatment	Tensile strength, lb /sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Izod impact, ft-lb.
Air cooled from 900°C. (1650°F.); tempered at 400°C. (750°F.)	147,000	115,000	20	45	30
Water quenched from 900°C. (1650°F.); tempered at 475°C. (885°F.)	194,000	170,000	3	16	14

After normalizing and tempering, the steel had properties equivalent to those of plain silicon-manganese steels that had been given a full heat treatment. The ductility of the quenched and tempered steel was relatively poor.

The torsional properties of a steel containing 0.34 per cent carbon, 0.92 per cent manganese, 0.20 per cent silicon, 0.51 per cent chromium, and 1.20 per cent tungsten were determined by Lyse and Godfrey.[394] Results are shown in Table 121.

Tensile data have also been obtained in conjunction with tests at elevated temperatures and are given later (see page 347). It would appear that tungsten has a relatively slight effect on chromium steels in the normalized condition, although it tends both to harden and toughen them. After full heat treatment, small amounts of tungsten behave somewhat like chromium but the effect is not so powerful. Larger amounts of tungsten appear to reduce strongly the ductility after heat treatment, although so few tests have been made that it is quite possible that balanced compositions and heat treatment were not used.

Because of its similarity to molybdenum, studies have been made to determine whether tungsten reduces the sensitivity to temper brittleness. Jones[162] reported that it had no effect in his steels. Houdremont and Schrader[391] in a study of chromium-nickel steels found that temper brittleness could be

developed in all steels by long holding at the tempering temperature. Tungsten had a tendency to retard embrittlement but was not so effective as molybdenum.

The effect of mass was studied by Kallen and Schrader[286] in sections up to 200 mm. (7.88 in.) in diameter. Two comparable

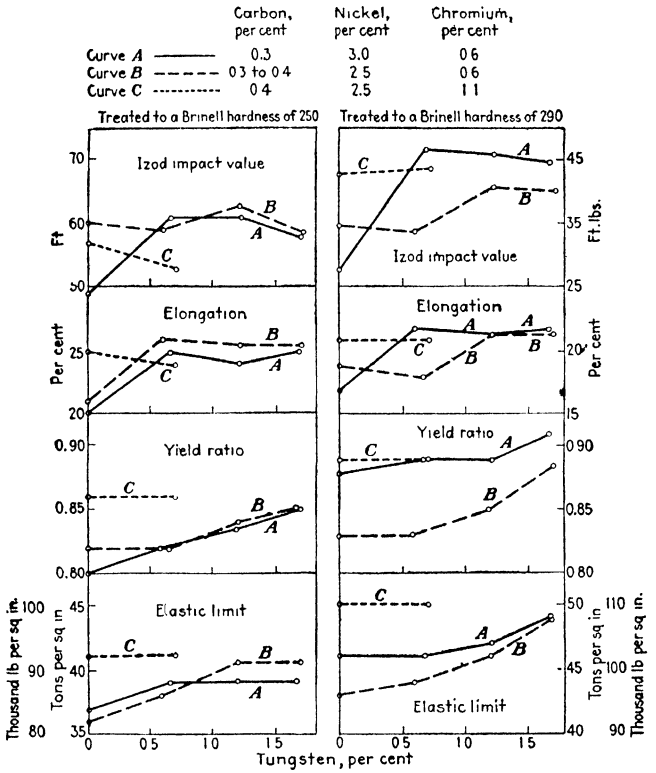


FIG. 119. - Properties of chromium-nickel-tungsten steels quenched and tempered to give Brinell hardness values of 250 and 290. (*Jones.*[162])

steels contained 0.3 per cent carbon and 4.1 per cent nickel, and, while one had 1.57 per cent chromium, the other had 1.16 per cent chromium and 0.97 per cent tungsten. The tensile properties were equivalent, but the tungsten-bearing steel was less affected by mass as indicated by the impact test.

140. Effect of Temperature on Mechanical Properties of Chromium-tungsten Steels.—Short-time tensile tests were made by Kahlbaum, Dowdell, and Tucker[330] on 2 per cent chromium

TABLE 121.—TENSILE AND TORSIONAL PROPERTIES OF A STEEL CONTAINING 0.34 PER CENT CARBON, 0.51 PER CENT CHROMIUM, AND 1.20 PER CENT TUNGSTEN*

Treatment	Tensile tests				Torsion tests			
	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Tensile strength, lb./sq in.	Yield point, lb./sq. in.	Modulus of elasticity, lb./sq. in.	Modulus of rigidity, lb./sq. in.
Furnace cooled from 790°C. (1455°F.)	82,500	48,000	40 0	56 0	84,900	42,000	28,500,000	12,700,000
Oil quenched from 870°C. (1600°F.) and tempered at 595°C. (1100°F.)	157,500		27 0	52 9	135,000	90,000	29,400,000	12,170,000

* Lyse and Godfrey [394]

steels containing tungsten of the compositions shown in Table 122. The results of the tests are given in Table 123. A gradual loss of strength was found with rise of temperature in the range tested.

TABLE 122.—COMPOSITION, SIZE, AND TREATMENT OF STEELS USED BY KAHLBAUM, DOWDELL, AND TUCKER[330]

Steel No.	Composition, per cent							Size of section	Treatment
	C	Mn	Si	Cr	W	V	Al		
*EE*1455	0 55	0 36	0 16	2 07	1 48			¾ in. round	Annealed
*EE*1456	0 55	0 41	1 26	2 10	1 61	0 29		¾ in round	Annealed
*EE*1454	0 53	0 46	0 24	2 05	1 54	0 26	1 75	¾ in. round	Annealed
*E*3226-*A*	0 36	0 62	0 19	2 47	2 00	0 23	.	Billet	Oil quenched and tempered at 590°C (1090°F.)
*E*3226-*B*	0 36	0 62	0 19	2 47	2 00	0 23		..	Oil quenched and tempered at 625°C. (1160°F)

Long-time creep tests have been made by a number of investigators. French, Kahlbaum, and Peterson[277] and Kahlbaum and Jordan[367] tested a series of 2 per cent chromium-tungsten steels with vanadium and molybdenum, and Spooner and Foley[346] gave creep data on chromium-tungsten (-vanadium) steels. In discussion of that paper, White and Clark and Coffin and Swisher gave values on several other chromium-tungsten steels. These data are summarized in Tables 124 and 125. Kanter also presented flow data on a similar steel.

White, Clark, and Wilson[443] reported creep data on a steel with 0.45 per cent carbon, 0.47 per cent manganese, 0.77 per cent silicon, 1.40 per cent chromium, 0.98 per cent tungsten, and 0.25 per cent vanadium, tested at 425, 540, and 650°C. (800, 1000, and 1200°F.). As shown in Table 125, their results agree fairly well with those previously mentioned.

It will be noted that these steels have a high degree of resistance to creep at temperatures up to 550°C. (1020°F.). At higher temperatures they are not capable of holding much load, but in the moderately elevated temperature range that is encountered in many chemical processes and steam plants, the chromium-tungsten steels represent about the best of the low-alloy steels. Accelerated creep tests have been made but are not of significant interest.

141. Chromium-tungsten Steel Castings.—Tests on a chromium-tungsten cast steel were made by Grotts;[86,139] the properties in Table 126 were taken from a graph of his results. Krieger[184] reported the use of 0.4 to 0.5 per cent carbon, 1.8 to 2.0 per cent chromium, and 1.2 to 1.5 per cent tungsten cast steel for rolls in the manufacture of seamless tubing. It was heat treated to give a tensile strength of 180,000 to 270,000 lb. per sq. in. with 8 to 12 per cent elongation.

TABLE 123.—SHORT-TIME TENSILE PROPERTIES OF 2 PER CENT CHROMIUM STEELS CONTAINING TUNGSTEN, VANADIUM, AND ALUMINUM*

Steel No.	Testing temperature		Tensile strength, lb./sq. in.	Proportional limit, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent
	°C.	°F.				
*EE*1455	20	70	111,500	66,000	21 2	52 2
	455	850	89,250	25,000	23 7	62 5
	510	950	79,750	17,250	25.0	66 5
	565	1050	62,750	10,150	30 7	79 4
	650	1200	49,750	3,000	26 2	80 8
*EE*1456	20	70	122,000	75,000	21 2	53 1
	455	850	95,600	29,000	24 7	61 1
	510	950	83,250	24,000	29 0	72 5
	565	1050	64,000	17,000	31 7	81.1
	650	1200	48,500	8,000	31.2	86.0
*EE*1454	20	70	104,500	66,000	17.7	34 4
	455	850	89,250	29,500	21 5	54 1
	510	950	80,350	23,000	23 0	61 1
	565	1050	68,000	13,000	28 0	74.1
	650	1200	49,250	8,750	32.7	84.3
*E*3226-*A*	20	70	201,000	152,000	15 0	52 8
	540	1000	113,500	32,500	15 0	56 4
*E*3226-*B*	20	70	132,000	96,000	17 0	52 0
	540	1000	84,000	28,000	22 0	73 4

* Kahlbaum, Dowdell, and Tucker.[330]

142. Uses of Chromium-tungsten Steels.—Chromium-tungsten steel in engineering grades is used almost exclusively for high-temperature service. It is suitable for hot-working dies, rolls,

TABLE 124.—CHEMICAL COMPOSITION AND ROOM-TEMPERATURE PROPERTIES OF STEELS WHOSE CREEP-STRENGTH VALUES ARE GIVEN IN TABLE 125

Investigator	Specimen No.	Composition, per cent						Quenching temperature		Cooled in	Tempering temperature		Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent
		C	Mn	Si	Cr	W	V	°C.	°F.		°C.	°F.				
French, Kahlbaum, and Peterson[277]	*EE*1139	0.46	0.37	0.19	2.20	1.65	0.25	950	1740	Oil	540	1000	231,500	207,000	7.8	22.8
Kahlbaum and Jordan[367]	*EE*1546	0.50	0.62	0.76	2.35	1.66	0.27	690	1275	Slowly	.	..	183,500	148,000*	13.2	38.5
	*EE*1554	0.28	0.49	0.38	2.24	1.92	0.29	690	1275	Slowly		.	167,500	138,000*	16.0	47.8
Spooner and Foley[346]	43	0.38	0.95		0.57	0.86		840	1540	Oil	650	1200	150,800			
White and Clark, in discussion[346]	*D*1	0.08	0.25	0.28	1.17	0.97										
Coffin and Swisher, in discussion[346].....	252	0.50	.	.	0.76	1.18	.	675	1245	Oil	425	795				
	253	0.50			0.76	1.18		650	1200	Oil	425	795				
	101	0.42	0.34	0.24	1.98	2.91	0.20	600	1110	Furnace						
	210	0.42	0.34	0.24	1.98	2.91	0.20	700	1290	Air	600	1110				
	209	0.36	0.30	0.19	1.38	1.98	0.19	700	1290	Air	600	1110				
	211	0.41	0.32	0.27	1.47	2.04	0.29	700	1290	Air	600	1110				
White, Clark, and Wilson[443] .	17–22	0.45	0.47	0.77	1.40	0.98	0.25	Normalized			705	1300				

* Proportional limit.

TABLE 125.—CREEP STRESS OF CHROMIUM-TUNGSTEN STEELS WHOSE COMPOSITION IS GIVEN IN TABLE 124

Investigator	Specimen No.	Creep in 1000 hr., per cent	Limiting stress at temperatures indicated, lb. per sq. in.							
			400°C. (750°F.)	425°C. (800°F.)	455°C. (850°F.)	480°C. (900°F.)	510°C. (950°F.)	540°C. (1000°F.)	595°C (1100°F.)	650°C. (1200°F.)
French, Kahlbaum, and Peterson[277]	*EE*1139	0 1			5,400			1,500*		
		1 0			7,200			2,000*		
Kahlbaum and Jordan[367]	*EE*1546	0 1	80,000		53,000		14,000	11,000†	4,500	
		1 0	102,000		81,000		37,000	16,500†	9 000	
	*EE*1554	0 1	101,000		76,000		24,000	21,000†	5,500	
		1 0	105,000		88,000		60,000	26,500†	15,500	
Spooner and Foley[346]	43	1 0		19,000		14,800		11,800		
White and Clark, in discussion[346]	*D*1	0 1						16,000		
		1 0						20,000		
Coffin and Swisher, in discussion[346]	252	1 0‡			11,800		6,550§			
	253	1 0‡			10,900		5,400§			
	101	1 0‡			38,000					
	210	1 0‡			26,900		12,500§	4,100*		
	209	1 0‡			39,000		21 000§	10,500*		
	211	1 0‡			36,000		16,600§	6,500*		
White, Clark, and Wilson[443]	17–22	1 0		96,000				42 500		2,700
		1 0‖		68,000				24,000		1,200
		1 0‡		48,000				13,800		500

* At 550°C (1025°F.).
† At 565°C. (1050°F).
‡ In 100,000 hr
§ At 500°C. (930°F).
‖ In 10,000 hr.

pressure vessels, and fittings that are to be used at temperatures up to 540°C. (1000°F.). The degree of high-temperature strength rises in proportion to the alloy content, but in the grade under consideration a substantial degree of hot strength is conferred by 1 to 2 per cent chromium and 1 to 2 per cent tungsten. Some application of tungsten has been made in reducing the susceptibility to temper brittleness of nickel-chromium steel for crankshafts.

TABLE 126.—MECHANICAL PROPERTIES OF CASTINGS CONTAINING 0.43 OR 0.48 PER CENT CARBON, 0.53 PER CENT MANGANESE, 0.95 PER CENT CHROMIUM, AND 0 49 PER CENT TUNGSTEN*

Quenched in oil from		Tempering temperature		Tensile strength, lb./sq. in.	Yield strength, lb./sq in	Elongation in 2 in , per cent	Reduction of area, per cent	Sclero-scope hard-ness
°C	°F.	°C.	°F					
870†	1600†			110,000	85,000	10 0		30
845	1550	540	1000	137,000	125,000	4 0	8 0	49
845	1550	600	1110	130,000	112,000	6 0	16 0	44
845	1550	650	1200	122,000	104,000	8 0	20 0	40

* Grotts [86 139]

† Cooled in the furnace

143. Miscellaneous Chromium Steels.—Several elements have been added to chromium steels with the intention of changing the character of the steel to suit it to some particular purpose. Aluminum, for example, has been added to obtain a harder case in nitriding steel, and cobalt is used in magnet steel which is discussed in a later chapter. The addition of high phosphorus to Cor-Ten, a chromium-copper-silicon steel, has been discussed in Chapter VIII (page 285). Tin has been added without much success. The deoxidizing elements have been successfully used to refine the grain and reduce the inclusion content.

Zirconium has been used successfully in a large tonnage of chromium-base steel. Zieler[353] carried out an investigation of inclusions in plain and zirconium-treated chromium-molybdenum steels and found by microscopic counts that zirconium effectively reduced the inclusion content. An addition of about 0.06 per cent zirconium is adequate to break up the inclusions. Zirconium is also effective in reducing grain size, the amount

required being somewhat more than is necessary with aluminum and less than is required with vanadium. In large amounts, 0.50 to 1 per cent zirconium, the steel is softened somewhat, but in the small amounts normally used for deoxidation the strength is unaffected and the ductility and impact strength are improved by the fine grain size.

Titanium has been added for much the same purpose. Tables 128 and 129 give mechanical properties determined by Arend and Lobe[380] on titanium-treated chromium and chromium-nickel steels of the analyses shown in Table 127. It was

TABLE 127.—ANALYSES OF STEELS USED BY AREND AND LOBE[380]

Steel No.	Composition, per cent					
	C	Mn	Si	Cr	Ti	Ni
3 Ti	0 14	0 72	0 29	0 77	0 18	
3	0 15	0 65	0 24	0 71		
4 Ti	0 18	0 71	0 34	0 73	0 36	
4	0 18	0 71	0 34	0 68		
5 Ti	0 13	0 52	0 31	0 78	0 26	3 47
5	0 13	0 58	0 25	0 60		3 50

found that titanium reduced the hardening capacity somewhat. The amount present (0.25 per cent) was much greater than would be used for grain-size control and, doubtless, better results would have been obtained with a smaller addition.

Gillett and Mack[154] reported mechanical properties of cerium-treated steels as shown in Table 130. The steels had the following composition:

Steel No.	Composition, per cent				
	C	Mn	Si	Cr	Ce
14	0 41	0 64	0 27	0 99	0 41 to 0 50
13	0 41	0 64	0 27	0 98	0 32 to 0 34

The properties were not particularly good and, on account of the erratic inclusion content, cerium steels have not been inves-

TABLE 128.—EFFECT OF QUENCHING ON BRINELL HARDNESS OF CHROMIUM-TITANIUM STEELS*

Quenching temperature		Quenched in	Brinell hardness			
°C.	°F.		Steel 3	Steel 3 Ti	Steel 4	Steel 4 Ti
As rolled			121	185	151	242
800	1470	Water	271	246	390	375
850	1560	Water	298	350	393	375
900	1650	Water	323	248	387	330
950	1740	Water	297	230	373	361
1000	1830	Water	274	248	382	361
1000†	1830†	Water	200	229	201	253
800	1470	Oil	222	171	366	274
850	1560	Oil	208	169	364	265
900	1650	Oil	223	198	366	279
950	1740	Oil	240	213	340	286
1000	1830	Oil	256	249	347	295
1000‡	1830‡	Oil	164	164	197	272

* Arend and Lobe (380)
† Tempered at 600°C (1110°F).
‡ Tempered at 650°C. (1200°F.).

TABLE 129 — TENSILE PROPERTIES OF CHROMIUM-TITANIUM STEELS*

Steel No	Condition	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation ($l = 5d$), per cent	Reduction of area, per cent
3 Ti	Rolled	77,000	57,500	25.6	68.5
3	Annealed at 800°C. (1470°F.)	64,300	51,400	29.0	67.0
3 Ti	Annealed at 800°C. (1470°F.)	70,700	51,400	29.0	70.0
3	Water quenched at 820°C. (1510°F.)	117,800	100,700	16.0	36.0
3 Ti	Water quenched at 820°C. (1510°F.)	112,000	68,700	20.0	42.0
3 Ti	Oil quenched at 820°C. (1510°F.)	97,700	57,800	18.0	41.0
4 Ti	Rolled	73,800	54,200	28.0	70.0
4 Ti	Annealed at 600°C. (1110°F.)	72,300	54,200	30.4	71.0
4 Ti	Annealed at 800°C. (1470°F.)	70,600	48,800	33.0	70.0
4 Ti	Annealed at 900°C. (1650°F.)	68,700	45,200	32.0	70.0
5	Annealed at 800°C. (1470°F.)	82,300	51,100	24.0	64.0
5 Ti	Annealed at 800°C. (1470°F.)	92,400	66,700	24.0	54.0
5	Water quenched at 850°C. (1560°F.)	175,400	164,700	12.0	38.0
5 Ti	Water quenched at 850°C. (1560°F.)	144,700	123,200	14.0	59.0
5 Ti	Oil quenched at 850°C. (1560°F.)	128,400	86,700	12.0	64.0

* Arend and Lobe.(380)

tigated further. Uranium-treated chromium steels were found some years ago to have good properties, but improved deoxidation with other elements has made these steels obsolete.

TABLE 130.—PROPERTIES OF CHROMIUM-CERIUM STEELS, OIL QUENCHED FROM 900°C. (1650°F.) AND TEMPERED*

Steel No.	Tempering temperature		Tensile strength, lb /sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness	Izod impact value, ft-lb.	Endurance limit, lb./sq in.
	°C.	°F.							
14	425	795	217,500	185,000	9 0	30 5	445	12 5	84,000
	525	975	149,500	130,000	17 0	54 5	325	40 0	72,000
	625	1155	119,500	90,000	22 0	60 0	245	52 0	59,000
13	425	795	211,250	175,000	11 0	40 3	440	11 0	
	525	975	148,250	135,000	16 5	53 3	280	35 0	
	625	1155	122,250	105,000	17 2	57 3	265	54 0	

* Gillett and Mack.[154]

D. AUTHORS' SUMMARY

1. The modified low-chromium structural and engineering steels discussed in this chapter are largely used in the normalized or fully heat-treated condition. One exception to this is found in the chromium-molybdenum steels used for the construction of transportation equipment in a manner similar to that of the structural steels mentioned in the previous chapter. Such use of the chromium-molybdenum steels is particularly prevalent in France.

2. The functions of molybdenum in reducing distortion on quenching, reducing mass effect, and resisting tempering are noted particularly in the chromium-molybdenum steels and account for their choice for many applications in the aircraft and automotive industries. These steels came into general use before the necessity of controlled grain size in automotive steels was appreciated and, owing to their method of manufacture, probably showed greater variation in grain size from heat to heat than many other competitive alloy steels. As a result, many metallurgists hold the opinion that chromium-molybdenum steels tend to give a wider variation in mechanical properties for a given analysis than do some of the competitive steels. The

introduction of grain-size control in the manufacture of these steels has remedied this situation. While their pronounced air-hardening qualities may frequently be desirable, there are many applications in which this characteristic is undesirable. However, the resistance to tempering is generally of advantage, allowing of higher tempering temperatures for a given hardness and resulting in lower internal stresses with improved impact strength in larger sections.

3. While a large tonnage of chromium-vanadium steels is used in the large forgings which are normalized, the greatest tonnage of these steels is found in the category of the fully heat-treated type used for automotive purposes. The naturally fine grain size and lack of susceptibility to variations in heat treating are the outstanding advantageous characteristics of these steels in most applications, and vanadium steels today are the only fine-grained steels that can be subjected to a commercially feasible heating to produce a coarse grain for machining purposes. The increased machinability of the coarse-grained material is sufficient so that the total cost of a great many pieces is lowered, even though the chromium-vanadium steels proper are of the most expensive variety. Thus, these steels are still used to a very large degree where one might expect them to be replaced by less expensive steels.

4. The use of vanadium in chromium-steel castings is a development which is rapidly growing. The statement has been made that all quality-steel castings should contain a minimum of 0.08 per cent vanadium, and this applies to the chromium steels as well as to other types. The reduction in segregation, suppression in dendritic structure, and finer grain are all produced by a small vanadium addition, with resultant improvement in mechanical properties.

5. While little has been reported regarding some of the more complex chromium steels containing both molybdenum and vanadium with or without nickel, silicon, and the like, such steels have been produced, and in mechanical properties and other attributes are the equal of any other commercial low-alloy steel.

6. Although the effect of tungsten on the mechanical properties of chromium steels seems to be slight, the strength at increased temperature is improved by the tungsten addition so that the chromium-tungsten steels are useful in dies and the like

where strength and hardness at moderately elevated temperatures are desirable features.

7. While the chromium steels treated in this chapter represent a smaller tonnage than that of the steels treated in the previous chapter, their mechanical properties are excellent. Wider use of these steels for some applications has been restricted by their higher initial cost although this is frequently more than offset by reduced fabricating costs and uniformity of product.

CHAPTER X

CHROMIUM TOOL STEELS CONTAINING LESS THAN 3.5 PER CENT CHROMIUM

High-carbon Low-chromium Tool Steels—Chromium Ball-bearing Steels—Chromium Die Steels—Miscellaneous Cutting and Forming Tools Containing Chromium—Authors' Summary

Any classification of tool steels is, at best, an arbitrary one. Compositions so defined by one individual are frequently mentioned by another in connection with applications quite definitely within the domain of engineering steels as, for example, ball bearings and gears. A definition, therefore, based on mechanical properties or chemical composition is scarcely appropriate. Again, the frequently diverse uses made of a given steel serve only to render the situation more complex. The term chromium tool steel as used in this monograph comprises that group of high-quality steels, usually in the upper carbon brackets, which contain chromium, alone or in combination with some other alloying elements such as vanadium, molybdenum, or tungsten, and which find definite application in machine tools or other highly specialized fields such as ball bearings, razors, and the like. It has been suggested by some of the reviewers of the first draft of the manuscript that, in order to obtain a true picture of the chromium tool steels, all other types of tool steels should be likewise discussed. While comparisons have been made in many instances, the reader is referred to the other monographs of this series for a discussion of those tool steels which do not contain chromium, or for a more complete discussion of such materials as high-speed steel in which chromium assumes a secondary rôle.

A. HIGH-CARBON LOW-CHROMIUM TOOL STEELS

144. Manufacture and Heat Treatment.—The particularly rigid requirements for these steels in their varied uses necessitate careful supervision throughout the manufacturing operation.

Although low-carbon chromium steels, such as S.A.E. 5120, are produced almost exclusively in the open-hearth furnace, it is only in comparatively few cases that the tool steels are made by any process save the crucible (now almost obsolete in the United States) or electric furnace. In open-hearth production the alloy is added after initial deoxidation, sufficiently long before the tap to allow complete melting and diffusion through the bath.

In basic electric-furnace practice, fine tool steels require a carefully selected charge of clean sponge iron, muck bar, or carefully selected scrap and pig iron and high-grade alloys, depending on the type of steel to be made. The charge should be melted with a high carbon content and should be mildly oxidized to eliminate impurities. After removal of the oxidizing slag, one or two carbide slags are built up to reduce the iron oxide present in the bath. The ferrochromium should be added early to assure complete melting and solution of carbides. A high grade of ferrosilicon is usually employed to complete the deoxidation. In acid practice similar care must be exercised to obtain freedom from oxides in the bath.

It is common practice in making tool steel to add chromium to the bath in the form of high-carbon ferrochromium, this being the most economical form in which the alloy is available. The grade most commonly used contains 5 per cent carbon, present in the form of chromium carbides. Viewed in the microscope, some of these carbides are present in comparatively massive form, and time is necessary for their proper solution in the steel bath. Matuschka[455] reported improved properties in chromium tool and die steels obtained by the use of the 2 per cent carbon grade of ferrochromium. The resulting finer carbides and probably the nature of these carbides as well contribute to better carbide distribution in the finished product. It is probable that the increased cost of the 2 per cent carbon grade of ferrochromium is warranted for steel to be used in parts involving important service, although this view is far from being universally accepted.

Tapping is carried out carefully to avoid contamination by the slag, and although the temperature in the furnace should be fairly high, the pouring temperature should be as low as is consistent with good teeming. The ingots should be as small as possible and the pouring rate slow. Cooling and reheating should be carried out slowly to avoid thermal stresses. While acid steel

is usually considered to be less liable to flake or hair-crack formation, extreme care in deoxidation and subsequent handling of ingots and blooms is necessary to avoid this defect. The ingot surface must be clean as there is little or no tendency for healing of cracks and scabs during subsequent rolling.

While little variation in hot-working practice is found necessary with the low-carbon chromium steels, carefully controlled conditions are required with the tool-steel group in order to insure a satisfactorily uniform product. The lower thermal conductivity and increased hardness even at relatively elevated temperatures necessitate a slower rate of heating to insure safety from cracking, although this is sufficiently similar to plain carbon tool steels. Both hot and cold working may be difficult if the chromium or carbon content is high. Pomp and Zapp,[398] however, reported that the addition of 0.75 per cent chromium produced favorable effects on the cold-drawing properties of a 1.0 per cent carbon steel. The strength was increased and the tendency to tear during drawing was greatly reduced. After annealing at 830°C. (1525°F.) wire could be reduced 46 per cent in a single draw. Schneider and Houdremont[148] discussed the recrystallization temperatures of a steel containing 1.05 per cent carbon and 0.80 per cent chromium; data from their work on the strength and reduction of area of cold-drawn specimens, as well as the effect of subsequent annealing, are illustrated in Fig. 120.

The chromium tool steels are commonly used in the heat-treated condition, the specific treatment depending almost entirely on the intended application. Generally speaking, those containing more than 1 per cent chromium are oil quenched. The presence of chromium causes an elevation of the Ac_1 temperature to the extent of 1.1 to 1.2°C. (2 to 3°F.) for each 0.1 per cent and a lowering of the eutectoid carbon content. The retention of austenite is a function of the cooling rate and must be given consideration with many chromium steels.

145. General Effect of Chromium on Mechanical Properties.—The normal effect of chromium upon the mechanical properties of carbon steel is to increase the hardness, as pointed out in earlier chapters. Although it is proposed to consider here the various compositions in the light of their specific applications, a few general data from the work of various investigators are

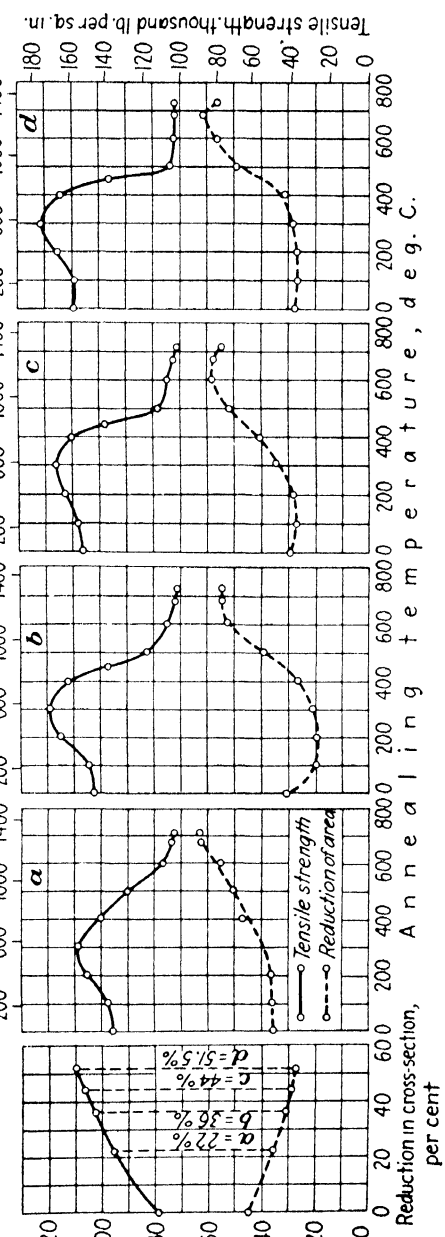


FIG. 120.—Influence of cold drawing and annealing on the strength and ductility of a steel containing 1.05 per cent carbon and 0.80 per cent chromium. (*Schneider and Houdremont.*[148])

presented in Table 131 to illustrate the effects within the ranges discussed. The practical significance, as well as the modifica-

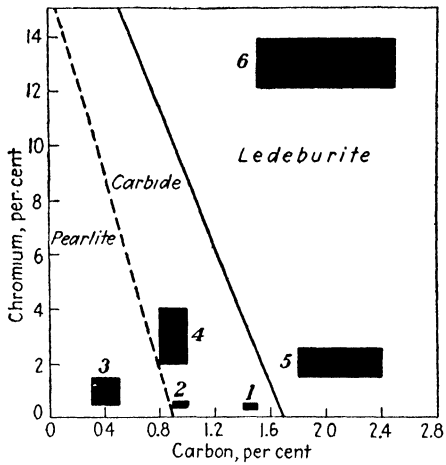


FIG. 121.—Application of chromium and chromium-tungsten tool steels. 1—Milling cutters, razors, saw files, stone-working tools, chisels, and the like; 2—twist drills, saw blades, lathe parts; 3—hand chisels and pneumatic chisels, drawing dies; 4—punches, dies, rolls for cold-rolling mills; 5—draw plates for low stresses; 6—draw plates for high stresses, parts for sensitive lathe and punching machines. (*Goerens.*[138])

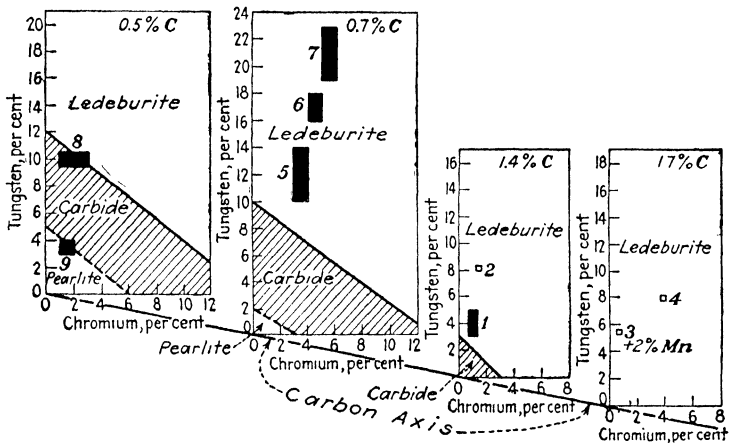


FIG. 122.—Principal types of tungsten-chromium tool steels. 1—Fast-finishing steel; 2—Midvale steel; 3—Mushet steel; 4—Taylor-White steel; 5, 6, 7—high-speed steels; 8—heavy-duty hot-die steels; 9—chipping chisels, cold punches, hot dies. (*Goerens.*[138])

tions in properties as brought about by the introduction of other elements, may then be considered. Goerens[138] has presented

TABLE 131.—MECHANICAL PROPERTIES OF HIGH-CARBON CHROMIUM STEELS AFTER VARIOUS TREATMENTS

Investigator	Composition, per cent		Tensile strength, lb /sq in	Yield strength, lb /sq in	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness	Impact value, ft-lb.	Treatment
	C	Cr							
Guillet[31]	0 97	0 99	187,000	187,000	3 5*	7 5	332	2†	As forged
	0 89	2 14	198,000	139,000	2 5*	0	364	3†	As forged
Austin[116]	0 87	2 08	136,500	89,500	9 0		277		Annealed
	1 00	2 09	135,500	67,200	9 0		269		Annealed
	1 26	2 11	122,500	67 200	19 0		241		Annealed
Arnold and Read[51]	0 84	0 99	97,250	42,400	22 5*	39 0			Annealed
Dickenson[73]	0 73	0 90	148,000	94,000	19 0	47 0			Quenched and tempered
	0 76	2 90	130,000	101,000	22 0	66 0			Quenched and tempered
Aitchison[92]	0 75	1 29	296,000						Oil hardened
	0 75	1 29	198,500	185,500	10 0*	27 6		9	Tempered at 500°C. (930°F)
	0 75	1 29	158,500	142,500	17 0*	45 9		25	Tempered at 600°C (1110°F.)
	0 75	1 29	142,250	123,500	20 0*	51 0		38	Tempered at 650°C (1200°F.)
	0 75	1 29	133,500	117,250	21 0*	52 2		48	Tempered at 700°C. (1290°F.)
	0 75	1 29	120,250	87,500	26 0*	58 0		38	Tempered at 750°C. (1380°F.)
McWilliam and Barnes[49]	0 85	2 0	159,000	116 600	12 0	34 4			Normalized
	0 85	2 0	89,750	42,500	32 0	63 5			Annealed
	0 85	2 0	214,500	208,500	8 5	28 2			Water quenched from 800°C. (1470°F.) and tempered at 550°C. (1020°F.)
	0 85	2 0	141,250	130,000	20 0	51 7	...		Water quenched from 800°C. (1470°F.) and tempered at 700°C. (1290°F.)

* Gage length not given.

† Reported in m-kg (Frémont bars)

graphically the various chromium and carbon ranges used in different tool applications as well as those for chromium, tungsten, and carbon in the more complex tool steels. These are illustrated in Figs. 121 and 122. In view of more recent practice, particularly in the steels included in groups 2 and 5, Fig. 122 should be modified by extending rectangle 8 to cover the range 8 to 15 per cent tungsten, and an additional rectangle covering the range 5 to 9 per cent chromium and 5 to 7 per cent tungsten should be included.* The 5 per cent chromium, 1 per cent tungsten, 1.5 per cent molybdenum type should also be mentioned in this connection.

B. CHROMIUM BALL-BEARING STEELS

Although the use of iron in bearings to reduce wear can probably be traced back many centuries, steel bearings of the type used today to reduce friction in moving parts were not introduced until the bicycle era. For this particular application they were of the simple cup and cone form. Ball bearings for general use are a somewhat later development owing to the many difficulties encountered in the production of perfect steel spheres. With the development of improved methods of ball manufacture, improved bearing design, and newer alloy steels, their use became widespread in general engineering practice, and today ball and roller bearings are found in all mechanical appliances from the smallest of children's toys to locomotive axle boxes and the movable turrets of the largest battleships.

146. Composition of Ball-bearing Steels.—Although ball-bearing steels of a number of different compositions are available at the present time, the high-carbon chromium type represents the greatest tonnage. The analysis range of this steel is given in Table 132. The exact composition depends largely on the size of the ball or race. As the size increases, the chromium content is raised. This results in greater uniformity of hardness. The carbon content of the ball is frequently somewhat lower than that of the race.

*According to a private communication from J. V. Emmons, received while this chapter was in press, rectangle 2 in Fig. 121 should indicate a carbon range of 0.90 to 1.30 per cent to conform with present-day practice for the 0.50 per cent chromium steels used for twist drills and lathe tools.

The prime requisites of ball-bearing steel are intense hardness and high compressive strength, and although these are obtained in the plain chromium type just mentioned, many manufacturers have modified the analysis by the addition of vanadium, molybdenum, or other alloys in an effort to bring about improvement in the ability of the material to withstand shock and fatigue stresses. Thus, S.A.E. 6195 steel (see Table 132) is frequently used for balls, rolls, and races. Kjerrman[202] and Robinson[206] have described other types (Table 132) which have given satisfactory results.

TABLE 132.—COMPOSITION OF BALL-BEARING STEELS

Type of steel	Composition, per cent			
	C	Cr	V	Mo
High-carbon chromium	0 90 to 1 15	0 75 to 1 70		
S.A.E. 6195	0 90 to 1 05	0 80 to 1 10	0 15 min	
Kjerrman[202]	1 00	1 77		0 21
Robinson[206]	1 00 to 1 10	1 10 to 1 30		0 30 to 0 50
Robinson[206]	1 00 to 1 10	1 30 to 1 50	0 20 to 0 40	
Greaves[449]	0 47	2 40		

The composition of a number of 6.3-in. diameter ball bearings from the race of a gun turret of a modern German battleship has been reported by Greaves.[449] This is also given in Table 132. The balls had been hardened to a Brinell of 250. The weight of the turret, 120 tons, was supported by 150 of these balls in a path 29 ft. 2 in. in length.

147. Manufacture and Heat Treatment.—Similar to tool steels the nature of the service of ball-bearing steel requires that it be of the highest quality and free from flaws such as pipes, seams, large or excessive non-metallic inclusions, and banding. The inspection tests on this type of steel are particularly rigid. In the production of balls the smallest sizes are made from wire. Slugs of the correct length are sheared off and cold pressed to approximate form. When the size of ball produced approaches 1 in., hot-drawn rods supplant the wire, and the balls are formed by upset forging. For the larger balls, hot-rolled bar stock is used and the slugs sheared off hot and blanked with a drop

hammer. After rough grinding they are heat treated, ground to within a few thousandths of an inch of the finished size, and subjected to inspection, after which final finishing takes place. Although the rings for ball races are sometimes cut from tubular material, the smaller sizes are oftener prepared by upset forging. The cost of the necessary roll equipment for the preparation of the tubes or the maintenance of a sufficient supply of stock of various dimensions makes the former method more expensive. Races prepared by the upset process are claimed to be superior to those machined, as the additional work improves the steel. The heading of the stock in the upsetting process is similar to that in the preparation of bolts or rivets except that, after the forming, the head is pierced, the center remaining on the bar and being used for the next forging.

Ball-bearing steels of the plain chromium type are hardened by heating to 790 to 845°C. (1450 to 1550°F.) and quenching in light oil or water. With the lower chromium content (about 0.80 per cent), satisfactory results are obtained by water quenching. The size of the section is an important factor, and the smaller bearings are quenched from the lower temperatures. Best results are obtained by tempering at a temperature of approximately 150°C. (300°F.). To procure maximum hardness and uniformity in the subsequent quenching operation, the steels should first be well annealed at 730 to 790°C. (1350 to 1450°F.) and slowly cooled.

Approximately the same treatment serves for the chromium-vanadium (S.A.E. 6195) steel, although a somewhat lower annealing temperature is recommended, namely 720 to 750°C. (1330 to 1380°F.). Kjerrman[202] obtained the highest hardness, Rockwell *C* 66, in the chromium-molybdenum steel mentioned on page 362, and in a plain chromium steel containing 1.01 per cent carbon and 1.54 per cent chromium, by annealing at 745°C. (1375°F.) and quenching in water from 840°C. (1545°F.). He has stressed the importance of the use of the lowest safe annealing temperature, because the subsequent hardening may then be effected at a lower temperature.

Complete spheroidization and uniform distribution of the carbides before quenching are important requirements in ball-bearing steel. Numerous failures resulting from flakes, segregation, and soft spots caused by decarburization have been reported.

148. Mechanical Properties of Chromium Ball-bearing Steels. Attainment of the required hardness and high elastic limit and compressive strength of ball-bearing steels is greatly facilitated by the presence of chromium. The uniformly fine and "normal" grain structure also promotes wear resistance. Although high

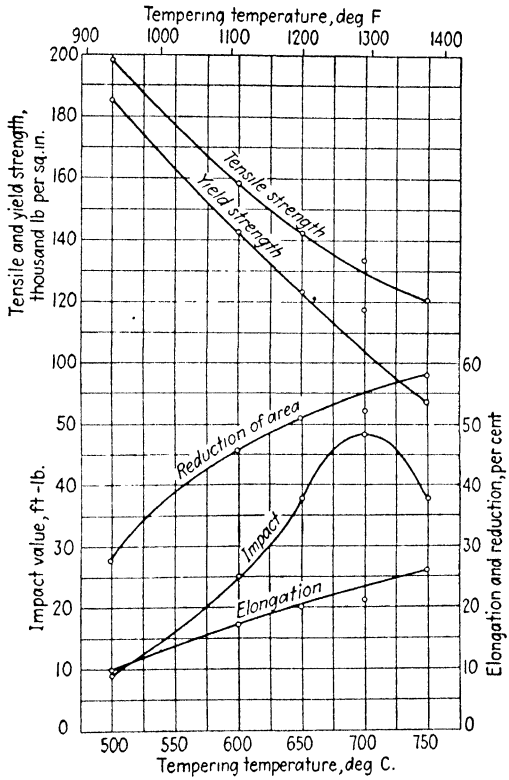


FIG. 123.—Variations in tensile and impact properties with tempering temperature in an oil-quenched steel containing 0.75 per cent carbon and 1.29 per cent chromium. (*Aitchison.*[93])

tempering temperatures are seldom used in bearings, the data included in Table 131, page 360, from the work of Aitchison,[93] and graphically presented in Fig. 123 are of interest in considering other possible applications of this steel. They illustrate the variation in tensile and impact properties with tempering temperatures.

Emmons[318] also made an extensive study of the effects of temperature on the hardening of tool steels. His work included

hardness and static torsion tests to determine ultimate strength and plasticity as well as microexamination of a steel containing 1.12 per cent carbon and 1.07 per cent chromium which had been hardened and tempered over a wide range of temperatures. His numerical data which are presented in Figs. 124 to 127, and which were supported by micrographic studies, illustrate the extreme responsiveness of this steel to heat treatment. Of special significance are the apparent zones of embrittlement following the peaks in the curves of "plastic deformation" and "toughness coefficient" which Emmons has compared with "blue brittleness." They would appear to indicate that, while the hardness follows inversely the tempering temperature, the toughness is not a direct function of the thermal treatment. The correlation of the mechanical properties and microstructure has been explained by him on the basis of the slip-interference theory of Jeffries and Archer.[142]

TABLE 133.—ENDURANCE AND BEND-TEST VALUES ON BALL-BEARING STEELS*

Specimen	Composition, per cent				Endurance limit, lb /sq. in.	Unit stress in bend test, lb /sq. in.	Rockwell *C* hardness
	C	Cr	V	Mo			
A	1 00 to 1 10	1 30 to 1 50			84,000	233,000	60 5
B	1 00 to 1 10	1 30 to 1 50	. . . .		88,000	220,000	59 5
C	1 00 to 1 10	1 30 to 1 50	0 20 to 0 40		94,000	290,000	59 5
D	1 00 to 1 10	1 30 to 1 50	0 20 to 0 40	. .	95,000	285,000	60 5
E	1 00 to 1 10	1 10 to 1 30		0 30 to 0 50	75,000	164,000	61 5
F	1 00 to 1 10	1 10 to 1 30		0 30 to 0 50	83,000	218,000	61 5

* Robinson.[206]

The elastic limit in compression of chromium steel of this type is approximately 419,000 to 364,000 lb. per sq. in. as compared with 323,000 to 220,000 lb. per sq. in. for carbon steel. The Rockwell *C* hardness, of the properly treated material, ranges from 65 to 68 and the scleroscope hardness from 100 to 110. Accurate Brinell values are not available as the standard-size Brinell balls are made of this material and flatten when used on the harder specimens. Robinson,[206] using a White-Souther machine and a special bend-test apparatus of his own design,

studied the fatigue and bend characteristics of a straight chromium steel, containing 1 to 1.10 per cent carbon and 1.30 to

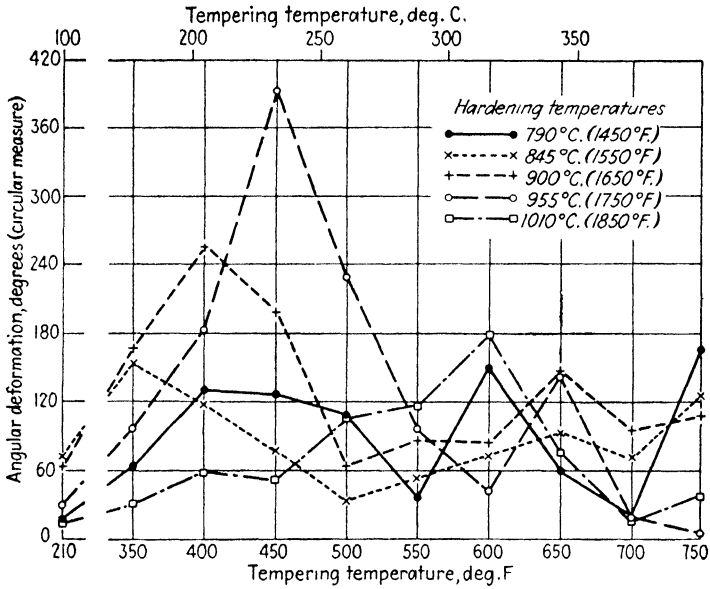


FIG. 124.—Effect of tempering on the plastic deformation of a steel containing 1.12 per cent carbon and 1.07 per cent chromium. (*Emmons.*[318])

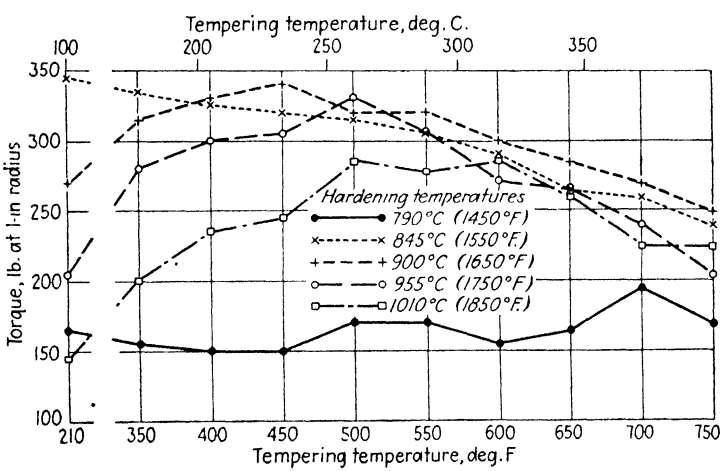


FIG. 125.—Effect of tempering on the ultimate torque of a steel containing 1.12 per cent carbon and 1.07 per cent chromium. (*Emmons.*[318])

1.50 per cent chromium, in comparison with the vanadium and molybdenum steels whose compositions are given in Tables 132

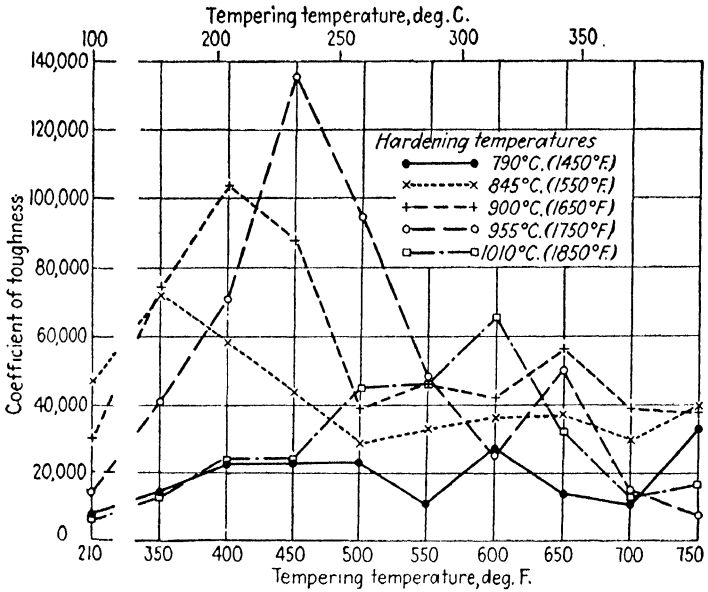


FIG. 126.—Effect of tempering on the coefficient of toughness of a steel containing 1.12 per cent carbon and 1.07 per cent chromium. (*Emmons.*[318])

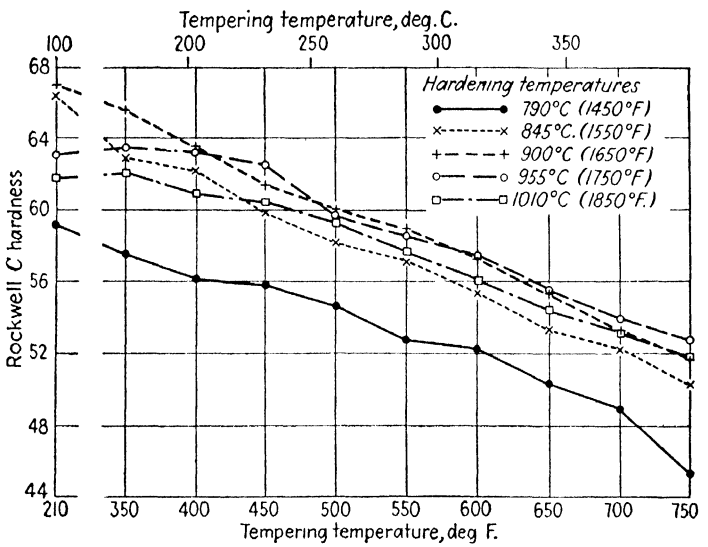


FIG. 127.—Effect of tempering on the Rockwell *C* hardness of a steel containing 1.12 per cent carbon and 1.07 per cent chromium. (*Emmons.*[318])

and 133. Although the numerical data vary little among the three steels, they group themselves similarly in each test, as did the microstructures. The molybdenum-containing alloys showed the greatest tendency toward carbide segregation while the greater uniformity of structure of the vanadium type was probably responsible for the better properties.

Shear and tensile tests on two high-carbon chromium steels have been reported by Portevin.[47] The results are as follows:

Composition, per cent		Elastic limit, in shear, lb./sq. in.	Resistance to shear, lb./sq in.	Elastic limit, in tension, lb./sq. in.	Tensile strength, lb./sq. in.	Reduction of area, per cent
C	Cr					
0 973	0 99	49,700	80,940		187,156	7 5
0 887	2.14	52,540	79,520	139,018	197,664	0

149. Wear Resistance of Chromium Ball-bearing Steels.—The resistance of high-carbon chromium steels to wear has been studied by Redenz[147] who used an Amsler machine, the tests being made without lubrication. The steels had the following compositions:

Steel	Carbon, per cent	Chromium, per cent	Note
1	1	1 2	
2	1 1	1 2	
3	1	1 5	Annealed at 735°C. (1355°F.)
4	1	1 5	Annealed at 775°C. (1425°F.)
5	1 2	1 5	
6	1	1 8	
7	1 2	1 9	
I	0 93		Rolled
II	0 93		Quenched and tempered

Redenz noted that aging at room temperature relieved the effects of cold work in the material and that the stresses had again to be built up before full wear resistance was regained. The peaks in the accompanying curve (Fig. 128) illustrate this point. Tests by Meyer and Nehl on 0.93 per cent carbon steel, included in Fig. 129 (steel I tested as rolled, steel II as quenched and tem-

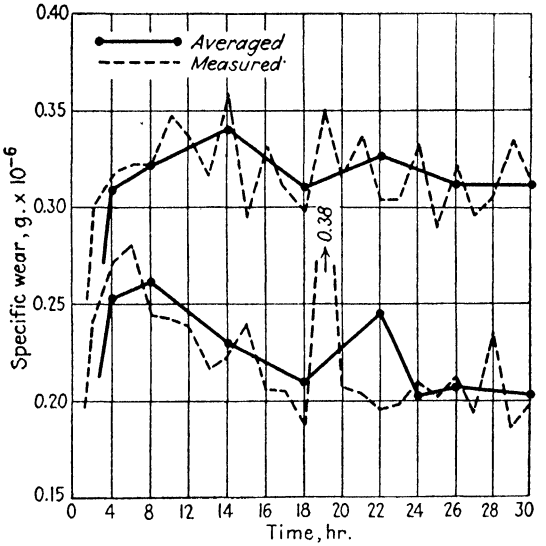


FIG. 128.—Specific wear of a hardened ball-bearing steel, containing 1 per cent carbon and 1.5 per cent chromium, under a load of 50 kg. (110 lb.). (*Redenz.*[147])

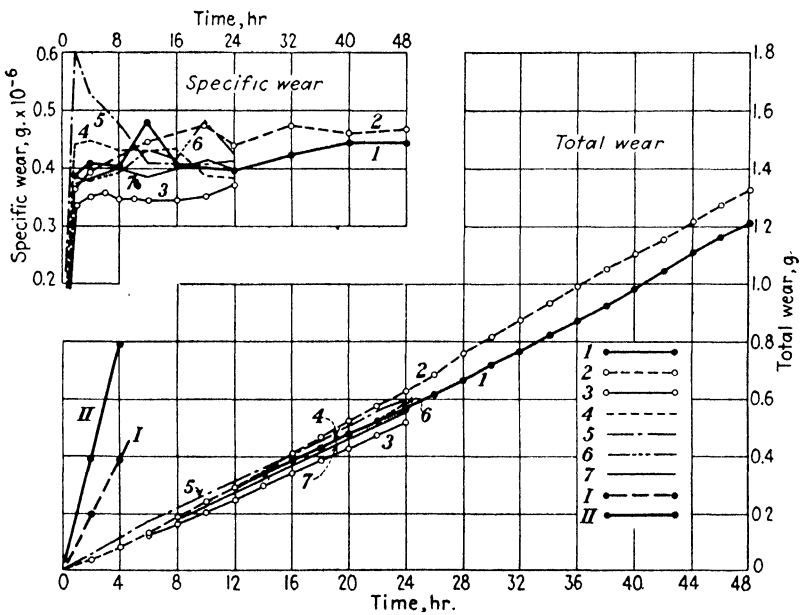


FIG. 129.—Comparison of the wear resistance of carbon and chromium steels. See page 368 for composition. (*Redenz.*[147])

pered), serve to indicate the improved wear characteristics of the chromium-containing steels. Brinell balls are frequently made of this type of steel and are superhardened by cold working.

C. CHROMIUM DIE STEELS

Die steels may be broadly classed under three headings, depending upon their intended use: cold-forming dies and punches; hot-forming dies, which include forging dies, gripper dies, and all those intended to handle solid material at elevated temperatures; and finally, die-casting dies which handle molten alloys. It is true that a given composition may often be used for more than one group, owing, for example, to the desire of a particular shop to keep only a limited number of steels in stock. If the choice has been wise, no serious difficulty will ensue. It is advisable, however, to exercise considerable care in the choice of die steels and their heat treatment as the expense usually involved in the preparation is many times greater than the cost of the material.

150. Cold-forming Die Steels.—In the cold heading of bolts and rivets, plain carbon steels are in general use. Jameson[282] has shown, however, that a small amount of chromium, *i.e.*, 0.12 per cent, lengthened materially the life of a die steel; he cited one containing 1.00 per cent carbon, 0.12 per cent chromium, 0.22 per cent silicon, and 0.45 per cent manganese. The improvement was due in a large measure to the somewhat deeper hardening brought about by the presence of chromium, although the addition of any larger quantity of this element or other alloy combinations, such as chromium and molybdenum, chromium and tungsten, and others which promote deep-hardening characteristics, resulted in increased failures due to the rapid progress of fatigue cracks through the hardened material. Many metallurgists believe that Jameson's work was too limited to permit definite conclusions to be drawn.

For general cold-stamping or blanking dies for both steel and non-ferrous alloys, such as are employed in coinage or the manufacture of jewelry or tableware, many chromium-containing steels are used. The important requirement for these steels is resistance to wear and deformation by pressure. In the case of the carbon steels, the depth of hardening is, of course, not great, and the brittle martensitic layer at the surface frequently spalls,

so that the addition of elements that lower the critical cooling velocity or permit deeper hardening of the steels is desirable.

Fabian[359] has described three German steels of the straight chromium, chromium-nickel, and chromium-nickel-vanadium types, the analyses of which are as follows:

No.	Composition, per cent					
	C	Cr	Ni	V	Si	Mn
1	1 5	1 75			0 25	0 50
2	0 45	1 50	4 0	0 50	0 25	0 50
3	0 35	0 50	3 0	1 00	0 25	0 50

Number 1 is usually tempered to a hardness of 66 to 67 Rockwell *C*. It is especially suitable for coins, medals, or jewelry that do not require too deep an impression. The steel is usually water quenched. This alloy is reported by Fabian to outlast by five times a carbon steel of similar character. For larger dies, such as might be used for spoons, forks, and the like, steel 2 is preferred. Its working life is much greater than that of an ordinary carbon steel because of its deeper hardening characteristics. It is hardened by air cooling from about 820°C. (1510°F.). Steel 3 is best suited for dies with deep impressions and is oil quenched from the same temperature.

In composition, American practice follows somewhat different lines, as may be seen from the data of Tables 134 and 135 which present a number of steels and their heat treatment as described by the American Society for Steel Treating[173] and the American Society for Metals.[463]

In Table 136 several analyses are presented of steels in general use in dies for the cold forming of steel and in punches. These steels are less subject to distortion in quenching than the water-hardening high-carbon chromium-vanadium steels formerly used and, because of their deeper hardening properties, give longer service under more severe operating conditions. While tungsten itself does not confer great hardness, the accompanying chromium brings about a combination of high hardness and properties not afforded by either element alone.

TABLE 134.—APPROXIMATE CHEMICAL COMPOSITION OF CHROMIUM AND CARBON DIE-BLOCK STEELS FOR SILVERWARE*

Steel No.	Composition, per cent†						Kind of work struck
	C	Si	Mn	Cr	Ni	V	
1	0 40 to 0 50	0 15 to 0 25	0 25 to 0 35	1 00	1 25	.	Steel
2	0 90 to 1.00	0 15 to 0 25	0.60 to 0 70	1 25	. . ..	0 25	Sterling, nickel flat ware, and steel
3	0 70 to 0 80	0 15 to 0.25	0 55 to 0 60	0.65 to 0 75	1.30 to 1.50	. .	Steel for small dies with shallow impressions
4	0.85 to 0.95	0 15 to 0.25	0.75 to 1 00	0 25 to 0 50	..... .		Oil-hardening jeweler's dies
5	0 85 to 1 00	0.25	0 25	. ...	....	. .	Steel, nickel silver, or sterling silver
6	1 00 to 1.15	0 25	0 25				
7	0 85 to 1.00	0.25	0 25	. .	.....	0 20	
8	1 00 to 1 15	0 25	0 25	. .	. ... ..	0 20	

* American Society for Steel Treating[173] and American Society for Metals [463]

† Sulphur and phosphorus are each required to be below 0.03 per cent for steel 1 and below 0.025 per cent for steels 2 to 4.

TABLE 135.—HEAT TREATMENT FOR STEEL DIE BLOCKS FOR SILVERWARE*
(Compositions given in Table 134)

Steel No.	Normalizing†			Annealing or spheroidizing‡			Hardening†			Tempering		
	Temperature		Cool in	Temperature		Scleroscope hardness	Temperature		Quenching medium	Temperature		Time, hr.
	°C.	°F.		°C.	°F.		°C.	°F.		°C.	°F.	
1	...	...	.	.	....	.	870 to 890	1600 to 1630	Oil	175	350	1
2	...	.	..	..	.	..	805 to 815	1480 to 1500	Water or oil	205 to 230	400 to 450	1 to 2
3	845 to 900	1550 to 1650	Air	720 to 745	1325 to 1375	35	770 to 795	1420 to 1460	Water at 50°C. (120°F)	230 to 275	450 to 525	1
4	800 to 830	1475 to 1525	Air	745 to 760	1375 to 1400	35	780 to 805	1440 to 1480	Oil	230 to 370	450 to 700	
5				745 to 775	1375 to 1425	..	845 to 870	1550 to 1600	Water or brine	175 to 290	350 to 550	
6	.	..		745 to 775	1375 to 1425		830 to 855	1525 to 1575	Water or brine	175 to 290	350 to 550	
7	.			745 to 775	1375 to 1425		845 to 870	1550 to 1600	Water or brine	175 to 290	350 to 550	
8	.	.		745 to 775	1375 to 1425		830 to 855	1525 to 1575	Water or brine	175 to 290	350 to 550	

* American Society for Steel Treating[173] and American Society for Metals [468]

† For normalizing and for hardening, heat 1 hr. for each 1 in of diameter or thickness and hold at temperature for one-fifth of heating time. When hardening, pack all dies in suitable carbonaceous material or place face down in a pan of carbonaceous material.

‡ Heat as for normalizing and hold 1 hr. for each 1 in. of diameter or thickness.

For dies of intricate design, an oil-hardening steel is generally used, the water-hardening type being safe only in the simpler sections. Steels of the non-deforming oil-hardening class, which contain more than a normal amount of manganese in addition to chromium or other alloying elements, are frequently used when slight dimensional change of the die during hardening is not

TABLE 136.—STEELS FOR BLANKING DIES AND PUNCHES*

No.	Composition, per cent					Annealing temperature		Quenching			Tempering temperature	
								Temperature		Medium		
	C	Mn	Cr	V	W	°C	°F	°C	°F		°C.	°F.
1	1 10 to 1 30	0 55 max.	0 50	0 20†	1 50	790 to 815	1450 to 1500	845 to 885	1550 to 1625	Oil	160 to 315	325 to 600
2	0 50		1 25	0 25	2 00	775 to 800	1425 to 1475	870 to 910	1600 to 1675	Oil	205 to 315	400 to 600
3	0 95	1 15 max.	0 50	†	0 50	775 to 800	1425 to 1475	790 to 815‡	1450 to 1500‡	Oil	150 to 290	300 to 550
4	0 85	0 35 max	3 75			815 to 845	1500 to 1550	925 to 980	1700 to 1800	Air	480 to 595	900 to 1100

* American Society for Metals (466)

† Optional.

‡ This steel should be heated very slowly but uniformly to a dark red heat of approximately 650°C (1200°F), then raised more rapidly but uniformly to the hardening temperature

permissible. This is often the case when, owing to intricacy of design, subsequent grinding is not practicable. The analyses of steels of this type are given in Table 137. The mechanical

TABLE 137.—COMPOSITION OF NON-DEFORMING OIL-HARDENING DIE STEELS*

Element	Percentage		
	No. 1	No. 2	No. 3
Carbon	0 85 to 1 00	0 90 to 1 00	0 85 to 1 00
Silicon	0 20 to 0 40	0 20 to 0 40	0 20 to 0 40
Manganese	1 15 to 1 45	0 90 to 1 15	0 95 to 1 25
Chromium	0 30 to 0 60	0 50 to 0 90	0 40 to 0 60
Tungsten	0 30 to 0 60		0 40 to 0 60
Vanadium	0 10 to 0 25		0 15 to 0 25†

* Gill, private communication.

† Optional.

properties of steel 1 as oil quenched and tempered are given in Fig. 130.

The 2 per cent carbon, 12 per cent chromium steels discussed in a later chapter (Volume II) are also used in this general application. One effective variety of cold-striking die which might be mentioned here, which is intermediate in character, contains 2.2 per cent carbon, 10.5 per cent chromium, 1 per cent tungsten, and 1 per cent silicon.

151. Hot-working Dies.—When the material to be worked or formed is above room temperature, a set of conditions arises that

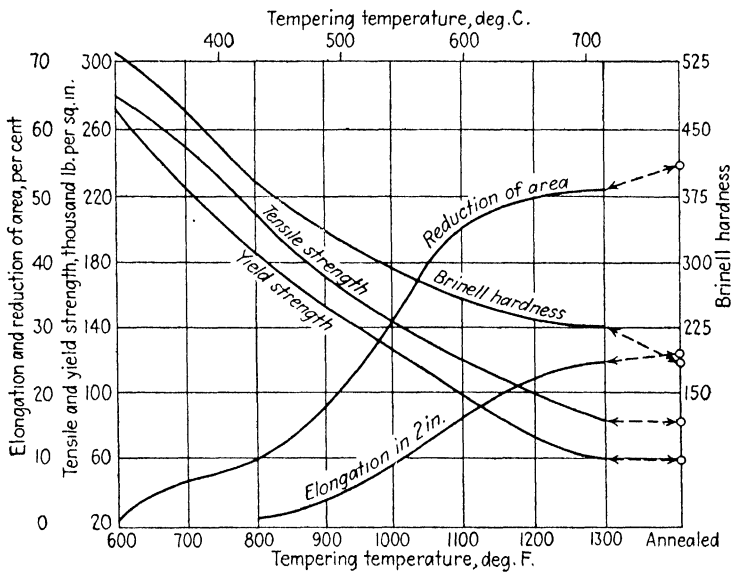


FIG 130.—Mechanical properties of steel 1, Table 137, oil quenched from 785°C. (1450°F.) and tempered as indicated. (*Courtesy of J. P. Gill.*)

requires different properties in the die steel which must retain its hardness and toughness and must withstand compressive stresses at high temperatures. To accomplish this, the composition must in many instances be altered by the addition of larger quantities of alloys or a proper balance of those present.

As a specific instance, the requisite properties of gripper dies may be compared with those used for hot heading. In the former example, the ability to retain hardness at heat is paramount, whereas in hot-heading dies, although hardness is more or less essential, toughness is also of major importance. Typical

analyses of steels for these applications are given in Table 138.* Steel 1 possesses good heat-resisting properties whereas No. 2 shows the greater toughness.

TABLE 138.—ANALYSES OF STEELS FOR GRIPPER DIES AND DIES FOR HOT HEADING*

Element	Percentage	
	No. 1	No. 2
Carbon	0.30 to 0 45	0.45 to 0 55
Tungsten	9.00 to 11 00	1.75 to 2.25
Chromium	2 50 to 3 25	1 00 to 1 50
Vanadium	0 40 to 0 60	0 15 to 0.30

* American Society for Metals [463]

Many of the steels used for hot-working dies contain more than 3.5 per cent chromium and are discussed later. Table 139 presents several recommended analyses for steels in the lower chromium ranges, together with their usual application. Their heat treatment is given as follows:[463]

The usual annealing temperature for all these steels is 760 to 790°C. (1400 to 1450°F.). The rate of heating should not be less than 1 hr. per in. of diameter or thickness, and the holding time at temperature is one-fourth of the total heating time. This is followed by slow cooling. All steels can be oil hardened from 800 to 845°C. (1475 to 1550°F.). The time for heating should be the same as for annealing, and the holding time at the hardening temperature should be one-fifth of the total heating time. Steel 4 may also be hardened by quenching from 845 to 900°C. (1550 to 1650°F.) in a fan blast. After quenching, these steels are tempered to the desired hardness.

Mechanical properties of a typical modified chromium die steel with chromium at 1.5 to 1.8 per cent are shown graphically in Fig. 131.

* While this monograph was in press, the Cleveland Twist Drill Company announced a new hot-die steel (*Steel*, v. 100, 1937, Mar. 15, p. 98) containing about 0.40 per cent carbon, 3.50 per cent chromium, 5.75 per cent molybdenum, 1.00 per cent tungsten, and 0.75 per cent vanadium. When hardened from 1225°C. (2240°F.) and tempered at 595°C. (1100°F.) it has a Rockwell *C* hardness of 56. According to Emmons (private communication), this steel is in regular production and is rapidly coming into general use. It shows excellent resistance to "washing, heat checking, and sucking."

A number of tungsten steels closely approximating high-speed steel in composition are frequently used in hot work where the requirements are severe. The tungsten content varies from

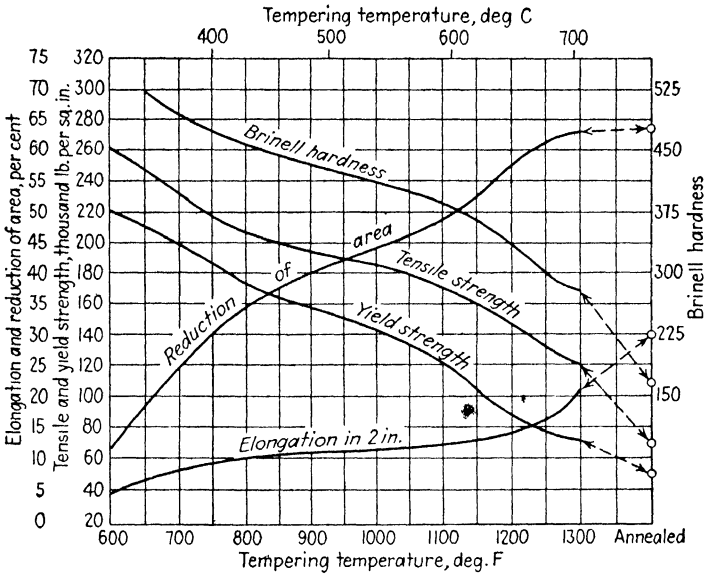


FIG. 131.—Mechanical properties of a die steel containing approximately 0.50 per cent carbon, 1.65 per cent chromium, and 2 per cent tungsten. (*Courtesy of J. P. Gill.*)

8 to 18 per cent and chromium from 1.25 to 4.5 per cent. The chromium, affecting both hardenability and toughness, must be carefully chosen for the specific requirement. The steels with lower chromium ranges are tougher, when drastically

TABLE 139.—APPROXIMATE CHEMICAL COMPOSITION FOR ALLOY-STEEL DIE BLOCKS*

Steel No.	Application or type	Composition, per cent					
		C	Mn	Cr	Ni	Mo	V
1	Drop hammer	0 50 to 0 70	0 50 to 0 90	0 60 to 1 30	1 00 to 2 00		Optional
2	Drop hammer	0 50 to 0 70	0 50 to 0 90	0 75 to 1 00		0 15 to 0 25	
3	Drop hammer	0 50 to 0 70	0 50 to 0 90	0 50 to 1 00	1 00 to 2 00	0 15 to 0 35	Optional
4	Oil or air hardening	0 50 to 0 70	0 50 to 0 80	0 75 to 1 00	1 50 to 2 50	0 60 to 0 90	Optional

* American Society for Metals.[463]

hardened, than those with higher chromium. A high-tungsten steel may be used at temperatures up to 595°C. (1100°F.) without appreciable softening. However, owing to their low thermal conductivity, these steels cannot be safely water cooled during operation. The effect of tempering on the hardness of a steel of this type is shown in Fig. 132.

152. Die-casting Die Steels.—In the case of die-casting dies some of the general hot-working die steels previously described are used even though operating conditions are quite different.

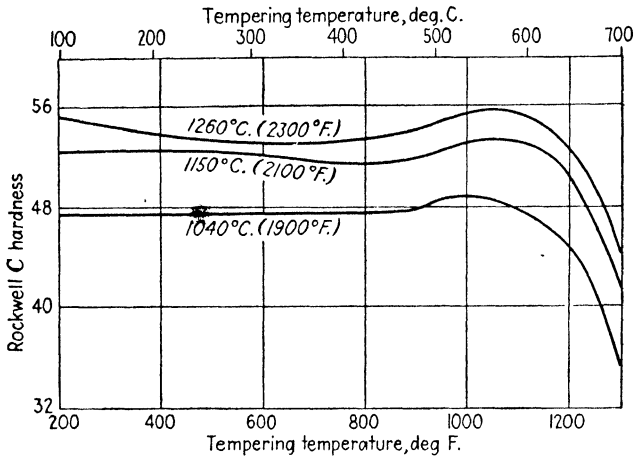


FIG. 132.—Effect of tempering on the hardness of a die steel containing 0.25 to 0.35 per cent carbon, 8 to 10 per cent tungsten, 2.50 to 3.50 per cent chromium, and 0.30 to 0.60 per cent vanadium. (*Courtesy of J. P. Gill.*)

Many of the desired properties are similar for all types of hot-die steels. In die-casting dies, however, the steel is subjected to more severe temperature changes, and more frequent alternations of temperature, which result in a greater tendency on the part of these dies to exhibit heat checking.

Tour[440] has defined the requirements of a good die-casting steel as follows:

1. Machinability.
2. Stability in heat treatment.
3. Resistance to heat checking.
4. Resistance to deformation, battering, and other mechanical pressure, *i.e.*, hardness.
5. Resistance to cleavage cracking on sudden heating or cooling, *i.e.*, toughness.

6. Resistance to erosive and solvent action of molten metals.
7. Cleanness and uniformity.
8 Cost—producibility; forgeability, and correlative properties.
9. Properties at elevated temperatures.

He made a number of elevated-temperature impact tests on a wide range of die-casting steels of the compositions and heat treatments given in Table 140. For testing the first four steels Tour used a standard Charpy impact specimen with a keyhole notch; for the last four a Charpy specimen with a 90-deg. V notch was used. The average impact values (of three tests) obtained

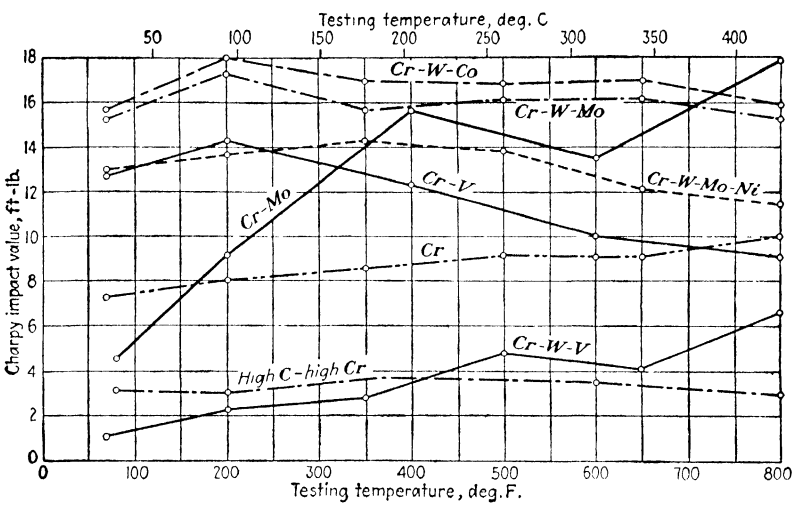


FIG. 133.—Elevated-temperature impact tests on various types of die-casting die steels. See Table 140 for composition and heat treatment. (*Tour.*[440])

at temperatures from 25 to 425°C. (75 to 800°F.) are plotted in Fig. 133. The chromium-tungsten-cobalt (No. 4) and the chromium-tungsten-molybdenum (No. 2) steel showed very good shock resistance at all the temperatures used. Tensile and distortion tests were also made on a number of steels.

Three of the more common die-casting die steels have the compositions shown in Table 141. In steel 2, 0.15 to 0.30 per cent vanadium and in No. 3, 0.30 to 0.60 per cent vanadium is optional. The applications and treatments recommended for these steels are:

Steel No. 1: Used for lead-, tin-, and zinc-base alloys Usually not heat treated although for zinc-base alloys heat-treated dies last longer.

TABLE 140.—COMPOSITION, HEAT TREATMENT, AND HARDNESS OF DIE STEELS TESTED BY TOUR[440]

No.	Steel	Composition, per cent									Quenching				Tempering temperature		Rockwell C hardness
											Temperature		Time at temperature, hr	Medium			
		C	Si	Mn	Cr	Ni	W	Mo	V	Co	°C.	°F.			°C.	°F.	
1	Cr-V	0.46	0.34	0.65	2.65	....	.	...	0.20		*	*				. . .	48
2	Cr-W-Mo	0.28	1.27		4.77		1.01	1.50	....	.	*	*				. .	46.5
3	Cr-W-Mo-Ni	0.33	. .		4.53	1.45	1.15	1.06	. .		*	*		. .		. . .	47.4
4	Cr-W-Co	0.34	0.96	0.33	5.11	.	5.36	.	. .	0.50	*	*			.		45.7
5	Cr-W-V	0.32	0.51	0.28	3.23	.	9.24	. .	0.47	.	1045	1910	5	Oil	575	1070	47
6	Cr	0.90	0.22	0.34	3.45	. .		. .			845	1550	5	Oil	445	830	46.5
7	Cr-Mo	0.50		0.65	0.70			0.35			845	1550		Oil	480	900	46
8	C-Cr-Mo-V	1.50	0.34	0.29	12.00			1.00	0.75		1040	1905		Air	†	†	46

* Heat-treated specimens supplied by Vanadium Alloys Steel Company.

† Tempering temperature not given.

Steel No. 2: Used for aluminum- and magnesium-base alloys. This steel is usually normalized or annealed as received from the manufacturer. If normalizing and annealing are necessary, heat slowly (1 hr. per inch of greatest thickness) to 925 to 980°C. (1700 to 1800°F.), hold for one-fifth of the heating time, and cool in still air. Reheat at same rate to 775 to 800°C. (1425 to 1475°F.) and cool slowly. The maximum Brinell hardness should be 207. For hardening, heat slowly (1 hr. per inch of greatest thickness) to 870 to 900°C. (1600 to 1650°F.), hold at temperature for the same time, and quench in oil at 25 to 50°C. (80 to 120°F.). Temper for 2 hr. per inch of greatest thickness at 425 to 480°C. (800 to 900°F.).

Steel No. 3: Used for copper-base alloys. This steel is not normalized but usually annealed as received from the mill. If annealing is necessary, heat slowly (1 hr per inch of greatest thickness) to 870 to 900°C. (1600 to 1650°F.), hold for two-fifths of the heating time, and cool in the furnace. Maximum Brinell hardness should be 235. For hardening, heat to 1040 to 1120°C. (1900 to 2050°F.), remove as soon as heated through, and quench in still air or oil at 25 to 50°C. (80 to 120°F.). Temper for 2 hr. per inch of greatest thickness at 565 to 650°C. (1050 to 1200°F.). (Air quenching is generally used because of less distortion, but oil gives better surface protection.)

TABLE 141.—COMPOSITION OF DIE-CASTING DIE STEELS*

No.	Composition, per cent				
	C	Mn	Cr	W	Ni
1	0 40 to 0 55	0 65 to 0 80	0 75 to 0 90		1 00 to 1 50
2	0 40 to 0 55	0 40 to 0 80	2 00 to 2 50		
3	0 25 to 0 40	0 20 to 0 35	2 75 to 3 50	8 5 to 10 5	

* American Society for Metals (463)

In die-casting steels as in those previously considered, many other compositions with higher chromium are in use where specific properties are desired that cannot be obtained with the lower alloy steels.

D. MISCELLANEOUS CUTTING AND FORMING TOOLS CONTAINING CHROMIUM

In this rather large class are considered chisels and general battering tools, cutting tools of all types, such as lathe, and hobbing tools, milling cutters, broaches, drills, woodworking tools, and saws, shear blades, and razors. Here especially, overlapping of compositions is found. Many of these tools, particularly those designed for straight cutting, are made of high-

speed steel, this composition being preferred also for many other tools. Owing, however, to economy factors in certain applications the lower alloy types find frequent use.

153. Chromium Steel for Chisels and Shear Blades.—The requirements for tools of this class differ considerably from those already discussed. As a rule, ability to retain a sharp edge together with more or less toughness is the essential characteristic desired. In many cases the analyses for even a single

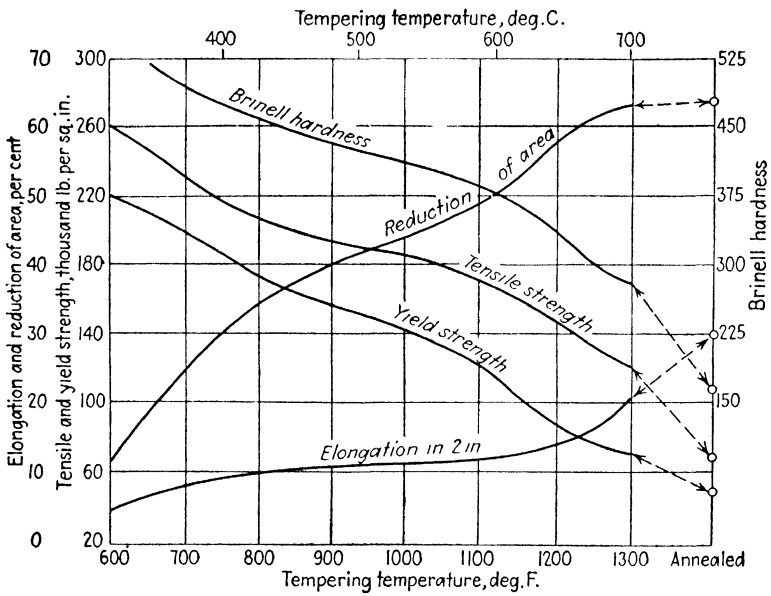


FIG. 134.—Effect of tempering on the mechanical properties of hardened steels containing 0.40 to 0.65 per cent carbon, 1 to 2 per cent chromium, 1 50 to 2.50 per cent tungsten, and 0.10 to 0.30 per cent vanadium. (*Gill.*[419])

type vary considerably, depending upon the specific application of the tool. For example, Gill[419] has described a series of four chromium-tungsten steels for use as chisels (see Table 142, steels 1 to 4). Steels of such compositions have also found application in punches, shearing blades, and battering tools.

In steel 1, vanadium has been added to improve the fatigue resistance of the steel. This composition, as well as that of steel 2, results in an extremely tough steel, which, even when hardened to a Rockwell *C* of 55 to 57, can be bent without breaking. In steels 3 and 4, silicon has been added to improve wear resistance, although with a considerable sacrifice in tough-

ness. The physical properties of steels of the general composition represented by No. 1 containing 0.50 per cent carbon are illustrated in Figs. 134 and 135. These steels may be oil or

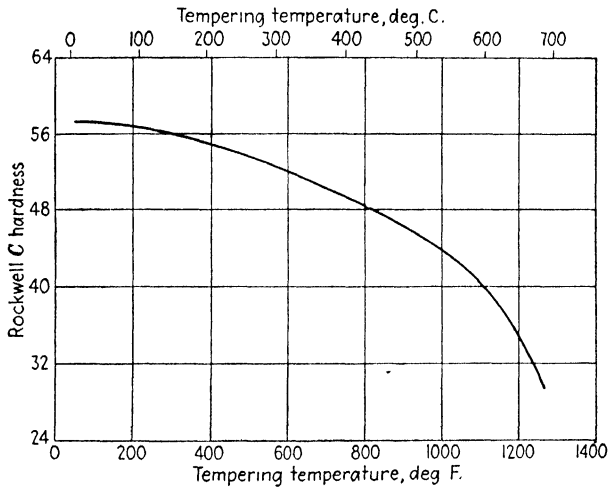


FIG. 135.—Effect of tempering on the Rockwell *C* hardness of the steels of Fig. 134. (*Gill.*[419])

water quenched, although the former is preferred. For oil hardening they are quenched from 870 to 900°C. (1600 to 1650°F.).

TABLE 142.—COMPOSITION RANGES OF CHROMIUM-ALLOY CHISEL STEELS*

Element	Percentage					
	1	2	3	4	5	6
Carbon	0 40 to 0 65	0 45 to 0 60	0 45 to 0 60	0 45 to 0 60	0 50 to 0 60	0 50 to 0 60
Manganese					0 70 to 0 90	0 35 to 0 60
Chromium	1 00 to 2 00	0 50 to 1 00	0 75 to 1 25	0 75 to 1 25	0 20 to 0 35	0 20 to 0 40
Tungsten	1 50 to 2 50	1 00 to 1 75	1 50 to 2 00	0 75 to 1 25		
Vanadium	0 10 to 0 30				0 15 to 0 30	
Silicon			1 00 to 1 50	1 00 to 1 50	1 75 to 2 25	0 75 to 1 25
Molybdenum						0 40 to 0 60

* Gill.[419]

A chisel steel of the general type represented by No. 1 but containing no vandium is also available for very much the same applications.

Gill[419] has also described a series of silicon-manganese steels for similar purposes, two of which contain chromium (see Table

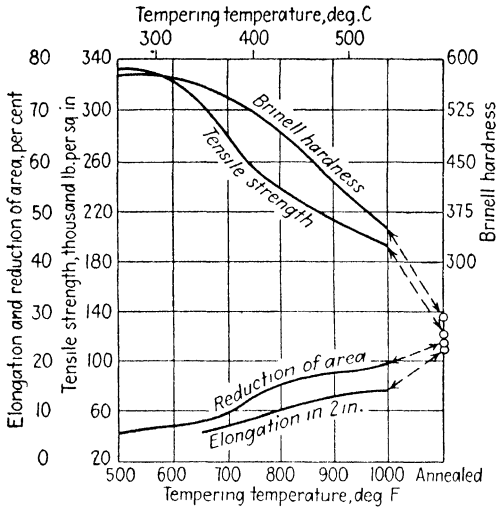


FIG. 136.—Effect of tempering on the mechanical properties of hardened steels containing 0.50 to 0.60 per cent carbon, 1.75 to 2.25 per cent silicon, 0.70 to 0.90 per cent manganese, 0.20 to 0.35 per cent chromium, and 0.15 to 0.30 per cent vanadium. (*Gill* [419])

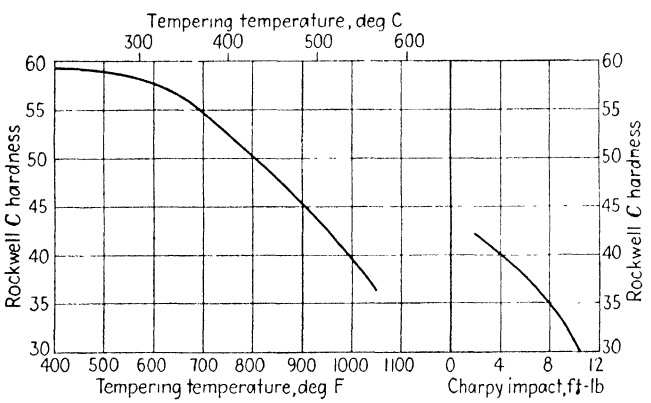


FIG. 137.—Relation between Rockwell *C* hardness and tempering temperature and between Rockwell *C* hardness and Charpy impact resistance for the steels described in Fig. 136. (*Gill.*[419])

142, steels 5 and 6). The properties of steel 5 after various tempering treatments are illustrated in Figs. 136 and 137. Steel 6 has a greater impact strength but lacks the wearing

properties of steels containing higher silicon. These steels are generally water quenched. On quenching from 885°C. (1625°F.), a Rockwell *C* value of 65 or 66 is obtainable with a carbon content of 0.71 per cent. The steel containing molybdenum may also be hardened by air quenching. The lower silicon content of this steel affords a greater freedom from decarburization than that found in steels containing 2 per cent of this element.

A somewhat different group of compositions for chisels has been described in connection with the recommended practice for heat treatment by the American Society for Metals,[463] as shown in Table 143.

Although the chisel steels discussed in this section are frequently used for shear blades too, the compositions presented in Table 143 represent the preferred analyses of chromium-containing steels for this purpose.[463]

154. Miscellaneous Chromium Tool Steels.—In the field of cutting tools, high-speed steel is most commonly used. This has been discussed in detail in an earlier monograph[420] of this series, and is taken up briefly in Chapter XI under special-purpose steels. For many operations, however, it is found more economical to use a lower alloy steel for cutting tools, and several compositions are available that have proved satisfactory. Among these are the so-called fast-finishing (occasionally known as semi-high-speed) steels, characterized by their ability to retain a keen cutting edge. A typical analysis and the usual heat treatment for this type are given in Table 144. Other steels, however, of even lower alloy content are in use though they are somewhat lacking in wear resistance.

A cutting tool with higher tungsten content (5 to 8 per cent), but still well below the high-speed-steel class, is recommended in German practice[214] for the removal of the hard outer layers of castings and for cutting grooves in rolls. The recommended analysis is given in Table 144.

In the manufacture of taps, broaches, drills, milling cutters, and other fine-edged tools, high-speed steel is generally used. As mentioned above, however, a lower alloy grade finds frequent application. A chromium-manganese-tungsten steel with vanadium optional (see Table 144 for composition and heat treatment) is described by the American Society for Metals[463] for many of these purposes. A low-chromium and a low chromium-molyb-

TABLE 143.—COMPOSITIONS AND HEAT TREATMENTS OF CHISEL AND SHEAR-BLADE STEELS*

Type	Purpose	Composition, per cent				Forging or annealing temperature†		Quenching			Tempering temperature		Scleroscope hardness
								Temperature		Medium			
		C	Cr	V	W	°C	°F.	°C.	°F.		°C.	°F.	
Chisel steels													
Cr-V	....	0 45 to 0 60	0 80	0 20		900 to 785	1650 to 1450	785 to 815	1450 to 1500	Water	175 to 290	350 to 550	
Cr	. ..	0 55 to 0 70	0 50		.	925 to 785	1700 to 1450	785 to 815	1450 to 1500	Water	175 to 290	350 to 550	
Cr-V-W	. .	0 45 to 0 55	1 25	0 25	2 00	950 to 815	1750 to 1500	900 to 925 to 840 to 870	1650 to 1700 to 1550 to 1600	Oil Water	150 to 260	300 to 500	
Shear-blade steels													
Cr-V	Cold work on light material‡	0 65 to 0 75	0 90	0 20		775 to 790	1425 to 1450	775 to 800 815 to 855	1425 to 1475 1500 to 1575	Water Oil	230 to 345 230 to 345	450 to 650 450 to 650	65 to 85 60 to 75
Cr-V-W	Cold work on medium and heavy materials	0 50	1 25	0 25	2 00	790 to 800	1450 to 1475	925 to 955	1700 to 1750	Oil	230 to 425	450 to 800	60 to 80
W	Hot shearing	0 40	3 50	0 40	10 00	870 to 900	1600 to 1650	1005 to 1175	1850 to 2150	Air or oil	600 to 675	1000 to 1250	50 to 60

* American Society for Metals (463)

† Forging temperatures for chisel steels, annealing temperatures for shear-blade steels

‡ Light material is stock ¼ in. thick or less, heavy material is thicker than ¾ in.

denum steel are recommended by Gill* for these small tools (see Table 144 for composition and heat treatment). These steels are both preferably hardened by oil quenching which

* Private communication.

TABLE 144.—COMPOSITION AND HEAT TREATMENT OF MISCELLANEOUS LOW-CHROMIUM TOOL STEELS

Type	Purpose	Reference	Composition, per cent						Annealing temperature		Quenching			Tempering temperature	
											Temperature		Medium		
			C	Mn	Cr	V	W	Mo	°C	°F	°C	°F		°C.	°F.
W-Cr-V	Fast finishing (semi-high-speed)	463	1 25 to 1 50		0 50 max	0 25 max	3 50 to 6 00		815 to 845	1500 to 1550	800 to 845	1475 to 1550	Water or brine	150 to 260	300 to 500
W-Cr-V*	Machining castings and rolls	214	1 20 to 1 40		1 00 or less	0 5 or less	5 0 to 8 0				800 to 820	1470 to 1510	Water		
Cr-Mn-W	Taps, broaches, drills, etc	463	0 90	1 10 to 1 50	0 50	0 20†	0 50		800	1475	790 to 815	1450 to 1500	Light oil	165 to 205	325 to 400
Cr	Taps, broaches, drills, etc	‡	1 15 to 1 25	0 50 to 0 70	0 45 to 0 55						815 to 845	1500 to 1550	Oil	See Fig. 138	
Cr-Mo	Taps, broaches, drills, etc	‡	1 15 to 1 25	0 75 to 0 95	0 45 to 0 55			0 50 to 0 70			815 to 845	1500 to 1550	Oil	See Fig. 139	
Cr*	Heavy-duty files	209	1 4		0 4 to 1 5			Nil	700 to 730	1290 to 1345	770 to 800	1420 to 1470	Saturated salt solution at room temperature		
Cr*	Metal-cutting saws	372	1 0		1 2			Nil			820 to 850	1510 to 1560	Oil	As desired	
Cr-W*	Metal-cutting saws	372	1 2 to 1 3		0 75 to 1 00		1 5 to 2 0	Nil							
Cr-Mo*	Fine-cutting tools	166	1 0 to 1 2		1 0 to 1 2			0 5 to 0 7							

* German steels
† Optional
‡ Gill, private communication

results in a file-hard cutting edge with a tough body and with a minimum of warpage on quenching. The mechanical properties to be expected from these steels after tempering are shown in Figs. 138 and 139. Typical compositions of several low-chromium steels representing German practice in the preparation of various types of tools are also included in Table 144.

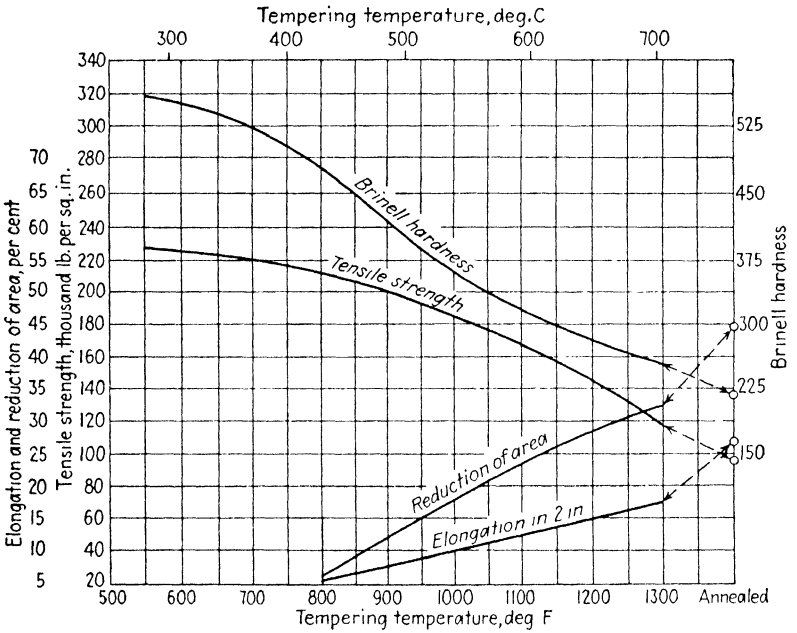


FIG. 138.—Mechanical properties of chromium steel after tempering as shown. The composition is given in Table 144. (*Courtesy of J. P. Gill.*)

Razor blades containing chromium have been reported by Desch and Roberts[121] to show a more uniformly distributed cementite and to have better cutting qualities than those in which the element is not present. Analyses of a number of blades obtained from various sources and examined by them are as shown in the table at the top of page 389.

The use of steels containing 0.85 to 0.95 per cent carbon and 1.75 to 2.00 per cent chromium for steel rolls is important although very little has been reported about this application. The combination of depth hardening and surface hardness renders this steel peculiarly fitted for service in cold rolling of strip steel[196] and of many non-ferrous metals.

Type	Make	Composition, per cent	
		C	Cr
Double-edged	German	1 29	0 82
Double-edged	American	1 39	Nil
Single-edged	Canadian	1 32	0 29
Double-edged	English	1 09	Nil
Double-edged	English	1 21	

E. AUTHORS' SUMMARY

1. The use of chromium in tool steels, either alone or in combination with one or more other elements is common, owing to the

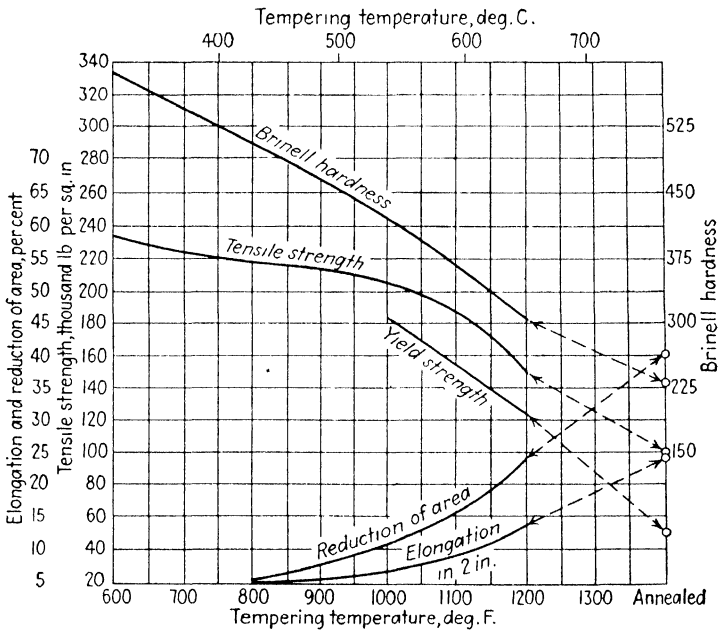


FIG. 139.—Mechanical properties of chromium-molybdenum steel after tempering as shown. The composition is given in Table 144. (*Courtesy of J. P. Gill.*)

desirable characteristics imparted to the steels. In steels to which chromium is added wear resistance is increased and the mechanical properties are improved; the depth-hardening ability, a property so necessary in die steels, is enhanced; increased toughness and hot hardness result.

2. The rational choice of a tool steel for a particular purpose is difficult, owing to the number of factors involved, and can be made only after a careful analysis of the problem on the basis of economy, tool design and preparation, type of operation, material to be worked, and other considerations. This is evident, as mentioned before, from the diversity of applications of a steel of a given analysis.

3. Although the compositions described in this chapter cover only those steels containing up to 3.5 per cent chromium, many other tool steels are in use in which this element is present in amounts up to about 15 per cent.

4. The functions of chromium as a hardening agent and a carbide former serve ideally in tool steels where high hardness without proportional loss of toughness is desirable. If these functions are considered in connection with the economics of their achievement, it is not surprising that chromium is a common element in tool steels; in fact, in present-day practice most tool steels contain chromium alone or in combination with other alloys. The increased hardness after heat treatment produced by chromium in a given mass serves to increase the wear resistance *per se*, and the presence of many finely divided carbides serves further to increase this property which is one of the all-important factors in the service of tools, ball bearings, or objects designed for similar applications.

5. Other elements, particularly vanadium, molybdenum, and tungsten, frequently used in conjunction with chromium in tool steels, serve further to accentuate both the reduction of mass effect on heat treatment and the finely divided character and number of carbides, at the same time serving further to toughen the matrix and to increase the retention of hardness at moderately elevated temperatures.

6. The use of chromium in hot-forming dies and the like is common. In such applications it may aid in reducing surface checking on heating and cooling, which in steels of this class is an important factor. The rôle of chromium in high-speed steels, as well as in steels of the high-speed type but containing lower quantities of tungsten, is of great economic importance. The susceptibility to heat treatment and the carbide distribution are both beneficially affected in these steels which are so dominant in the field of lathe-cutting tools.

CHAPTER XI

SPECIAL-PURPOSE LOW-CHROMIUM STEELS CONTAINING UP TO 3.5 PER CENT CHROMIUM

Nitriding Steels—Chromium Magnet Steels—High-speed Steel—Armor Plate and Other Special-purpose Chromium Steels—Authors' Summary

Among the special-purpose low-chromium steels are several which are important commercially although they are not used so widely as are the low-chromium structural steels, or even the low-chromium tool and die steels. All of these special materials, with the exception of the chromium magnet steels, contain one or more other alloying elements, and in some instances the other elements predominate in amount and effect. When this is so, as is especially evident in high-speed steel, and to a lesser degree in armor plate, the discussion in the present chapter is limited to viewing the specific effects of chromium upon the properties, leaving to other monographs a complete summary of the structure and properties of these materials.

The special-purpose steels which form the subject matter of the present chapter include nitriding steels, chromium magnet steels, high-speed steels, armor plate, steels for high-pressure chemical apparatus, and ferritic carburizing steels.

A. NITRIDING STEELS

The affinity of chromium for nitrogen and the formation of a nitride of chromium have long been recognized, having been described by Ufer[9] as early as 1859. His observations have been confirmed by many later investigators who have shown that chromium steels absorb more nitrogen when heated in an atmosphere of nitrogen or ammonia, and evolve more nitrogen under vacuum heating, than do the plain carbon steels. Microexamination and other data indicate that this nitride formation is largely a surface-layer phenomenon, the high nitrogen contained in the metal near the surface tending to inhibit further penetra-

tion into the steel. In this respect, chromium steel has been shown to be similar to steels alloyed with such other elements as aluminum, molybdenum, vanadium, etc.

This retarding of nitrogen penetration has been made the basis of the nitriding process as described by Fry.[123] Special steels containing elements which retard nitrogen penetration are treated with ammonia or other nitriding agents at temperatures below the lower critical temperature of the steel with the resulting production of a hard case, surpassing in hardness those obtained by the usual carbon-cementation methods. The low temperature of treatment eliminates distortion in properly treated material.

155. The Nitriding Process.*—The process in common use at the present time for the surface hardening of special steels by nitriding is to subject the parts to be treated to an atmosphere of ammonia for periods varying from a few to 90 hr., depending upon the depth of case desired, at temperatures from 450 to 580°C. (840 to 1075°F.), the latter representing the peritectoid temperature as defined by Fry.†

The treatment is sometimes carried out in special furnaces having gas-tight muffles and fitted with proper accommodations for the inlet and outlet of the ammonia. In some cases, fans are provided to permit more efficient circulation with a resulting greater uniformity of gas composition. In other installations the material is packed in metal chips in containers through which the ammonia gas is passed, the whole being placed in the furnace for the actual nitriding treatment. Here again perfectly gas-tight seals must be maintained in order to insure best results.

Since the inception of nitriding, the inconvenience of the long cycle has been recognized, and many workers have studied the problem of reducing the required nitriding time.[246,249,270,287,293,357]‡ The depth of case desired is dependent upon the type of service for which the parts are intended, varying from less than 0.001 in. to about 0.03 to 0.04 in.

* The nitriding process has been discussed in some detail in a previous monograph,[360] "The Alloys of Iron and Molybdenum" Chapter X, in connection with the use of molybdenum in nitriding steels.

† A. Fry, German Patent 386,510, Jan. 28, 1921, and U. S. Patent 1,487,554, Mar. 18, 1924.

‡ See also H. W. McQuaid, U. S. Patent 1,804,176, May 5, 1931.

156. Chromium in Nitriding Steels.—From the very earliest work of Fry,[123] the presence of chromium was recognized as being essential to a good nitriding steel even though aluminum steels after nitriding were shown to possess a considerably greater hardness than any others. This was due to the difficulty met with in the manufacture of steels of uniformly good quality, with high aluminum content. The handicap is largely eliminated by the addition of chromium, since the presence of this element lowers the amount of aluminum necessary to produce a given hardness.

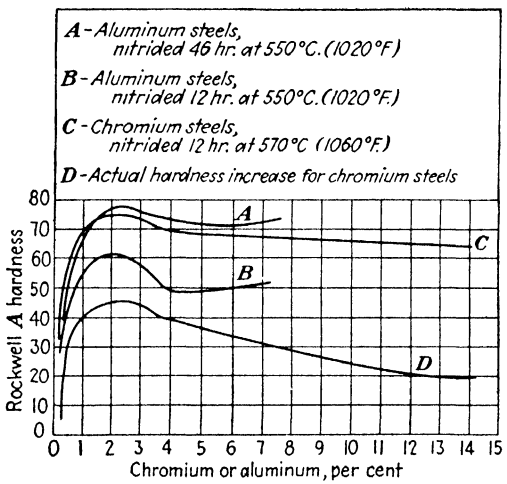


FIG. 140.—Effect of chromium and aluminum on the Rockwell *A* hardness of nitrided case. (*Eilender and Meyer.*[274])

Among the early analyses were steels containing about 2 per cent chromium with aluminum closely approaching this value. While they showed a high degree of hardness in the case, their physical characteristics and manufacturing difficulties left much to be desired. Further work in the laboratory and mill soon resulted in the modified analyses that are used at the present time. In the aluminum steels both the chromium and the aluminum contents have been lowered, and molybdenum has been added. Other types have been developed, such as the chromium-vanadium steel described by Kinzel.[220]

Table 145 gives the composition of some of the chromium-containing nitriding steels described by various investigators.[325]

They may be grouped in the following classes: chromium-aluminum, chromium-aluminum-molybdenum, chromium-aluminum-nickel, and chromium-vanadium. In some instances these analyses have been chosen for a particular purpose, as, for example, No. 13 when an especially hard core is desired or No. 12 for exhaust valves in internal-combustion engines. Steel 17 is a modification of a standard analysis, sulphur having been added to improve the machining properties of the steel.

With straight chromium steels the hardness of the case increases with the alloy content, the maximum being obtained at 2 to 3 per cent chromium. Owing, however, to the extremely slow penetration of the nitrogen in these steels, the case obtained after the usual nitriding cycle is comparatively shallow and does not possess the high hardness or other desirable case characteristics obtained when the chromium steel is modified by the addition of other elements. The curves of Fig. 140, taken from the work of Eilender and Meyer,[271] show this variation of hardness* of case with increase in chromium content.

157. Mechanical Properties of Nitriding Steels.—To obtain the most satisfactory mechanical properties of both case and core, nitriding steels are generally heat treated before the nitriding operation. This treatment serves not only to bring about optimum core properties but also eliminates the dangers of distortion in the finished material. It is advisable that all machining be completed before nitriding and after other heat treatment. The preliminary treatment usually consists of an anneal followed by oil quenching and tempering at a temperature higher than that to be used for nitriding. The mechanical properties of many of the steels listed in Table 145 are given in Table 146. Figures 141, 142, and 143 illustrate the variation in core properties of the more common nitriding steels with change in tempering temperatures.

158. Hardness of the Nitrided Case.—The unusual hardness of the case produced by the nitriding of carbon steels was recognized, even before Fry's work on alloy steel, by Machlet.† He

* The Rockwell *A* hardness given in Fig. 140 is obtained with the Brale penetrator and a 60-kg. load. A description of Rockwell *A* hardness and its relation to other Rockwell hardness values is given in "Metals Handbook,"[463] pp. 24–26.

† A. W. Machlet, U. S. Patent 1,065,379, June 24, 1913.

TABLE 145.—COMPOSITION OF PRINCIPAL NITRIDING STEELS*

No.	Composition, per cent					Authority and reference
	C	Al	Cr	Mo	Other elements	
1	0 10	1 00	1 50			Homerberg and Zavarine[216]
2	0 40	0 80	1 60			Homerberg and Zavarine[216]
3	0 36	2 03	1 62		0 10 Ni	McAdam[334]
4	0.30	1 30	1 60		1 40 Ni	Homerberg and Zavarine[216]
5	0 25 to 0 40	1 0		0 80 to 1 0		Merten,[227] McQuaid and Ketcham[224]
6	0 25	1 0 to 1 4		0 60 to 1 0		Colonial Steel Company[268]
7	0 26 to 0 31	1 0 to 1 2		0 15 to 0 25		Herbert[280]
8	0 10 to 0 20	0 60 to 1 2	0 80 to 1 3	0 15 to 0 25	†	Sergeson and Clark[344]
9	0 20 to 0 30	0 60 to 1 2	0 80 to 1 3	0 15 to 0 25	†	Sergeson and Clark[344]
10	0 30 to 0 40	0 60 to 1 2	0 80 to 1 3	0 15 to 0 25	†	Sergeson and Clark[344]
11	0 55 to 0 65	0 60 to 1 2	0 80 to 1 3	0 15 to 0 25		Sergeson and Clark[344]
12	0 45 to 0 60	0 25 to 1 0	7 0 to 9 0	0 40 to 1 0	1 0 to 2 0 Si	Colwell[269]
13	0 18	. . .	3 00	0 40	. . .	Fry[242]
14	0 38	Nil	0 11	Nil	0.49 V	Kinzel.[220] Private communications to Harder
15	1 50	..	12 to 14	1 0	1 0 V	Private communications to Harder
16	0.27	....	1 50	... ...	0 50 V	Kinzel, in discussion of paper by Kinzel and Egan[287]
17	0 37	1 06	1 07	0 19	0 15 S	Sergeson[300]

* Harder.[225]

† Some manufacturers report about 0.50 per cent nickel in these steels.

TABLE 146.—MECHANICAL PROPERTIES OF NITRIDING STEELS*
(Table 145 shows composition and authority)

No.	Tempering temperature		Tensile strength, lb /sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness	Impact value, ft-lb.		Reference No.
	°C.	°F.						Charpy	Izod	
1	540	1000	77,000	48,000	30	69	170	62		216
	650	1200	69,000	50,000	35	75	150	72		216
2	540	1000	191,000	172,000	13	40	390	12		216
	650	1200	148,000	126,000	18	54	320	34		216
3	650	1200	148,000	108,000	18	54				334
4	540	1000	168,000	150,000	14	45	365	14		216
	650	1200	132,000	112,000	20	57	285	31		216
5	540	1000	161,000	137,000	18	60	340	29		224
6	540	1000	120,000	100,000	20	67	260			268
	650	1200	105,000	85,000	24	73	225			268
7	500	930	157,000	134,000	15		410			215
	620	1150	108,000	92,000	30		260			215
8	540	1000	111,000	96,000	20	68	241		86	344
	650	1200	95,000	75,000	24	73	202		110	344
9	540	1000	146,000	131,000	14	53	330	20	40	344
	650	1200	122,000	105,000	18	65	255	25	75	344
10	540	1000	182,000	165,000	12	44	351	17	34	344
	650	1200	139,000	121,000	20	38	270	30	70	344
11	540	1000	206,000	183,000	11	36	450		18	344
	650	1200	159,000	137,000	16	49	330		40	344
12 to 15	Data not available.									
16	540	1000	150,500	137,000	17 5	59	311		32	†
	595	1100	148,000	134,000	20	61	311		38	†
	650	1200	131,000	120,000	21	63	277		75	†
	705	1300	98,000	89,500	26	73	217		103	†
	730	1350	92,000	85,500	30	75	187		112	†
17	Properties compare favorably with No. 10									300

* Harder.(325)

† Courtesy of Crucible Steel Company of America.

showed that a treatment of ordinary carbon steel with ammonia produced unusually hard, though extremely brittle, corrosion-resistant surface layers. Many investigators have reported on the hardness of nitriding steels. Figures 144 and 145 show data obtained by Hengstenberg and Mailänder[279] and Homerberg

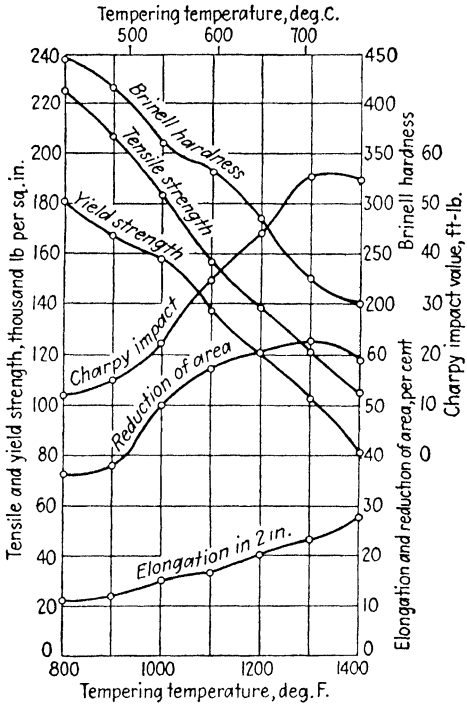


FIG. 141.—Effect of tempering on the mechanical properties of 1-in. round bars of Nitralloy *G* containing 0.36 per cent carbon, 0.51 per cent manganese, 0.27 per cent silicon, 1.49 per cent chromium, 0.010 per cent sulphur, 0.013 per cent phosphorus, 0.18 per cent molybdenum, and 1.23 per cent aluminum, oil quenched from 955°C. (1750°F.). (*Associated Alloy Steel Company*, 1930 *catalogue.*)

and Walsted.[329] The composition of the steels used by Hengstenberg and Mailänder is given in Table 147. Figure 146 gives the comparative hardness-depth relationship of chromium-vanadium and chromium-aluminum steels as determined by Union Carbide and Carbon Research Laboratories, Inc.

The nitrided case of the chromium-vanadium steel has shown a very desirable characteristic in its increased ductility over the chromium-aluminum type. This is illustrated in the photo-

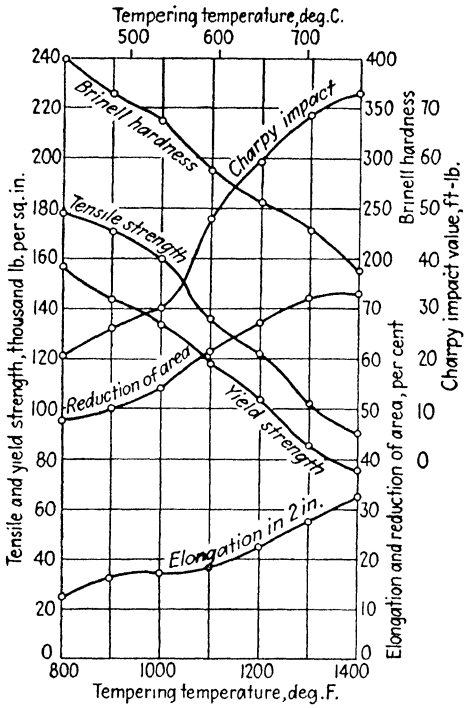


FIG. 142.—Effect of tempering on the mechanical properties of 1-in. round bars of Nitralloy *H* containing 0 23 per cent carbon, 0 51 per cent manganese, 0.20 per cent silicon, 1.58 per cent chromium, 0.011 per cent phosphorus, 0.011 per cent sulphur, 0.20 per cent molybdenum, and 1 24 per cent aluminum, oil quenched from 955°C. (1750°F.). (*Associated Alloy Steel Company*, 1930 *catalogue*.)

TABLE 147.—COMPOSITION OF NITRIDING STEELS USED BY HENGSTENBERG AND MAILÄNDER[279]

Steel	Composition, per cent						
	C	Si	Mn	Cr	Al	Ni	Mo
FP 15	0 30	0 43	0 41	1 43	1 12		
FP 13	0 52	0 14	0 27	1 74	1 28		
FP 13A	0 52	0.14	0 27	1 74	1 28		
FPK 13	0 32	0 22	0 72	1 24	0 93	....	0.34
FPE 23	0 42	0 19	0 38	1 68	1 33	2.65	
FK 345	0 15	0 25	0 4	0 85	.		0 41

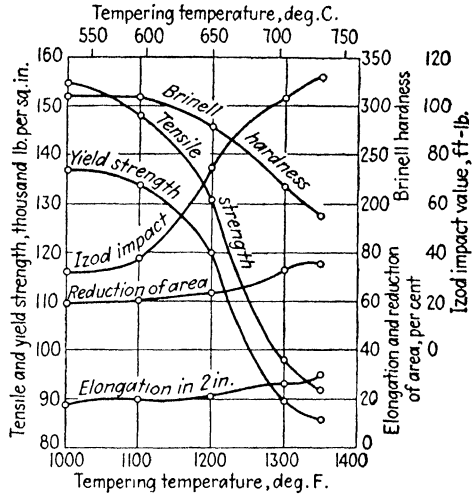


FIG. 143.—Effect of tempering on the mechanical properties of 1-in round bars of chromium-aluminum-molybdenum nitriding steel containing 0.37 per cent carbon, 0 15 per cent sulphur, 1.07 per cent chromium, 0 19 per cent molybdenum, and 1.06 per cent aluminum, oil quenched from 900°C (1650°F.). (*Crucible Steel Company of America*, 1931 *catalogue*)

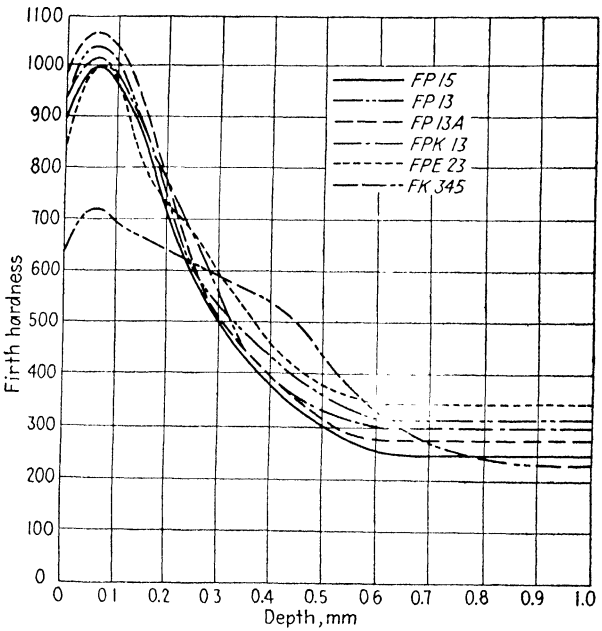


FIG. 144.—Depth-hardness curves of nitriding steels, nitrided 48 hr. at 500°C. (930°F.). Compositions are given in Table 147. (*Hengstenberg and Mailander.*[279])

micrographs (Fig. 147, page 402) of 500-kg. Brinell impressions on a steel of this type and on a standard chromium-aluminum steel. The chromium-aluminum nitrided case has cracked around the edges as well as at the center, while the nitrided case of the chromium-vanadium steel is still intact. A comparison of the scratch and Brinell hardness values of various steels and alloys with those of nitrided steel has been made by Malcolm[250] (Fig. 148).

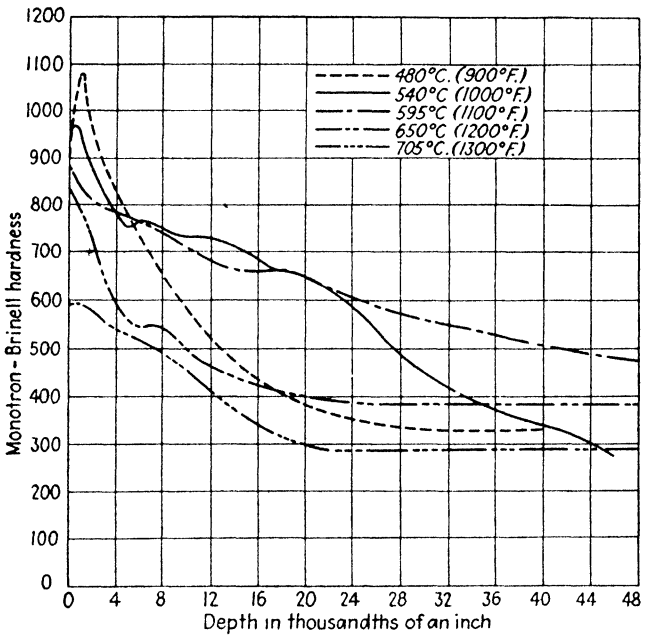


FIG. 145.—Depth-hardness curves of tapered specimens of Nitralloy G, nitrided 48 hr. at temperatures shown. See Fig. 141 for composition. (*Homerberg and Walsted.*[329])

Comparative hardness values of carburized and nitrided steels are graphically illustrated in Fig. 149, the original data having been reported by Fry[242] and by Sergeson.[259] The maximum surface hardness in the case of the carburized nickel-molybdenum steel was approximately 800 Brinell, whereas hardness values in excess of 1100 are obtained with many of the nitriding steels. Guillet[199] has shown that upon heating carburized and nitrided steel specimens to temperatures up to 600°C. (1110°F.) the nitrided case retains much of its hardness.

Herbert[280] (Fig. 150) reported on the hardness of nitrided steel at elevated temperatures in comparison with a high-speed steel and 1.2 per cent carbon steel. From his data it is seen that up to about 400°C. (750°F.) there is no appreciable loss in hardness in the nitrided steel. Above this temperature, however, the hardness falls rather rapidly, while the high-speed steel shows no appreciable loss at temperatures lower than about 600°C. (1110°F.). Even at this temperature, however, the

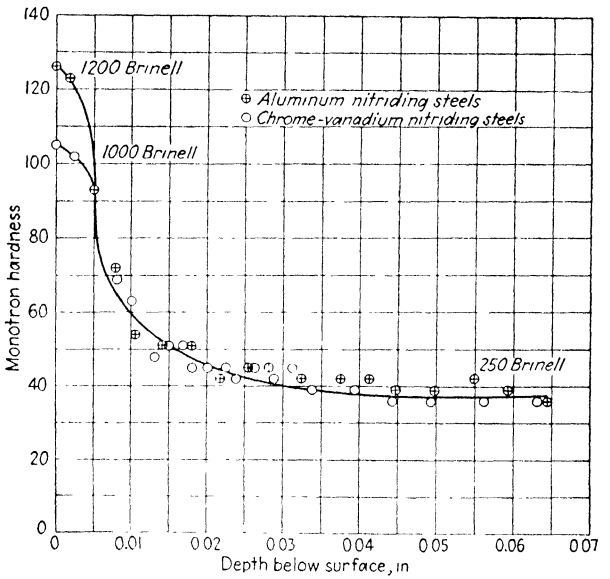


FIG. 146.—Depth-hardness curves of nitrided chromium-vanadium (steel 16, Table 145) and aluminum steels (steels 8 to 11, Table 145), nitrided 50 hr. at 460°C. (860°F.). (*Union Carbide and Carbon Research Laboratories, Inc.*)

hardness of the nitrided steel is still almost equal to that of the high-speed steel.

Many complex alloy nitriding steels have been studied including chromium-molybdenum-aluminum and chromium-molybdenum-vanadium types. The latter have been reported in detail by Strauss and Mahin.[457]

159. Wear Resistance of Nitrided Steels.—Many investigators have studied the resistance of nitrided steel surfaces to wear, using apparatus of varying design. Homerberg and Walsted[329] have described work by themselves and others at the Massachusetts Institute of Technology in which nitrided specimens

were subjected to wear involving translatory as well as rotary motion, with extremely promising results. Guillet[1299] and Malcolm[2501] have also found the wear resistance of nitrided

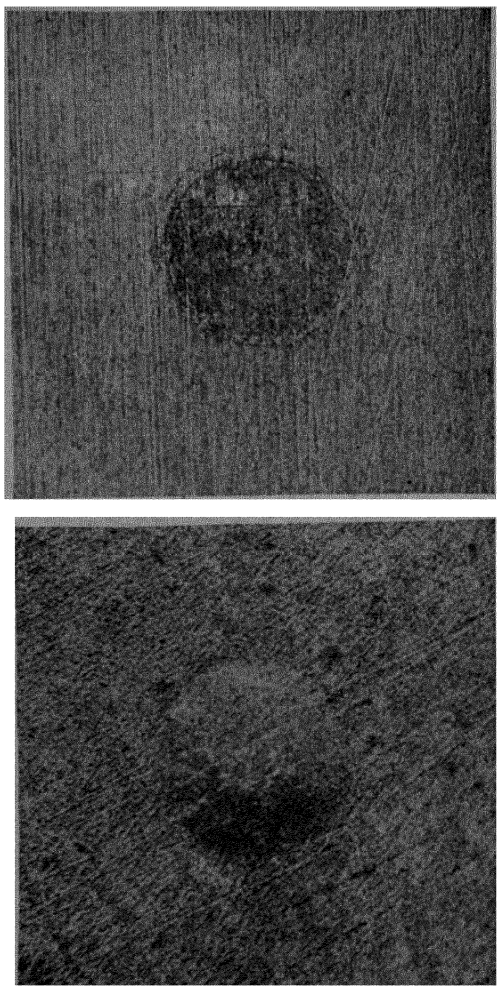


FIG. 147.—Brinell impressions in case of nitrided steel. *A*—No cracks in chromium-vanadium nitrided case. *B*—Cracks in less ductile nitrided case of chromium-aluminum steel. (*Union Carbide and Carbon Research Laboratories, Inc.*)

Nitralloy* to be high. The latter investigator reported that a stainless steel was badly abraded in his apparatus after 1000 revolutions, but under the same pressure, namely 200 lb., nitrided

* See Fig. 141 for approximate composition.

specimens showed comparatively little wear in 100,000 revolutions.

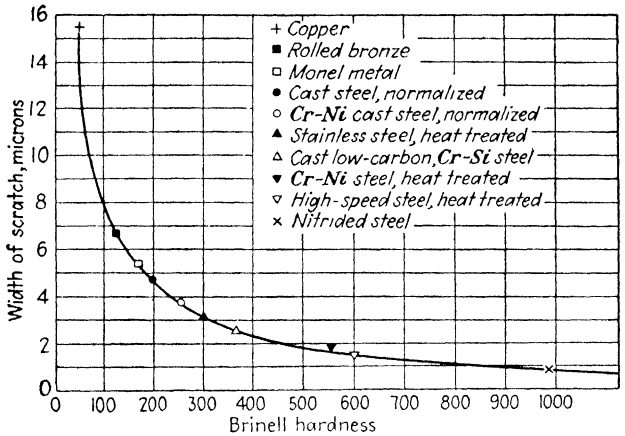


FIG. 148.—Comparison of the Brinell hardness of various metals in its relation to scratch hardness (*Malcolm* [250])

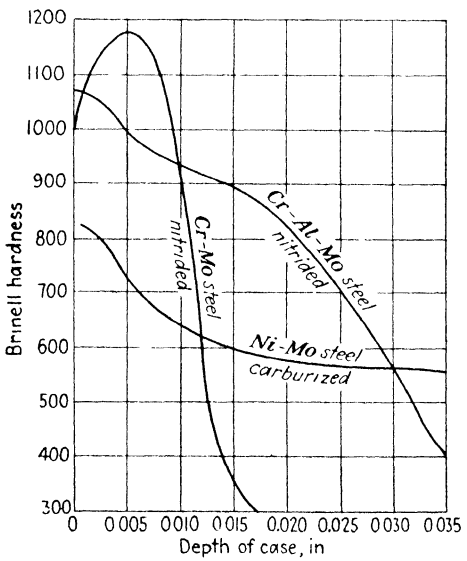


FIG. 149.—Hardness-depth curves for nitrided and carburized cases. (*Fry*[242] *and Sergeson.*[259])

Kinzel and Egan[249] studied the wear resistance of the thin cases produced by their accelerated cyanide-nitriding treatment, using one of these specimens as a rotating shaft in an open

cylinder filled with rusty water, the shaft passing through a stuffing box so adjusted as to permit a slow leak. After 17,000,000 revolutions, an ordinary machine steel failed through excess wear, while the nitrided specimen, even after 66,000,000 revolutions, showed neither wear nor corrosion, and the test was stopped. In another type of apparatus reported by Egan[357] nitrided specimens of chromium-vanadium and chromium-aluminum steels were subjected to wear involving a reciprocating motion of the nitrided face against surfaces of other materials. An

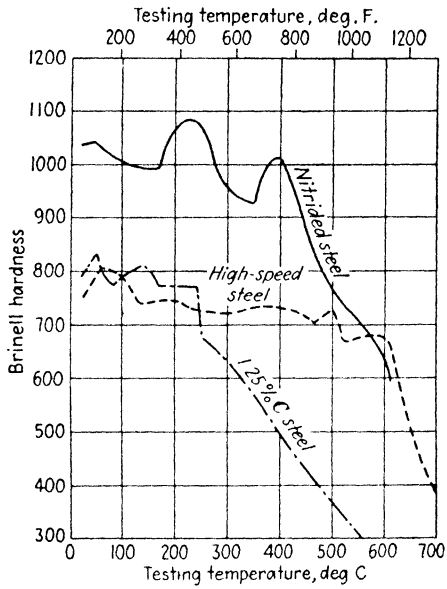


FIG. 150.—Hardness at elevated temperatures of nitrided steel, high-speed steel, and quenched high carbon steel. (*Herbert.*[280])

excellent wear-resistant combination of materials was noted in nitrided chromium-vanadium steel and stellite. The efficacy of nitrided steels in preventing seizing, another form of wear, is also recognized.[228]

160. Elevated-temperature Properties and Endurance.—Malcolm[250] tested nitrided chromium-aluminum steels in tension at 540°C. (1000°F.) under a load of 10,180 lb. per sq. in. An extension of 0.002 in. occurred in the first 4000 hr., with no increase during the succeeding 5000 hr. of testing.

The general results of investigations published on the endurance properties of nitrided steels indicate that the endurance

limit is high, being of the order of 85,000 lb. per sq. in. at room temperature. Fuller[278,321] determined the endurance limit in an atmosphere of steam, finding no decrease at temperatures up to about 370°C. (700°F.).

Mochel[295] reported on the properties, including fatigue, of a steel containing 1.67 per cent chromium, 0.91 per cent aluminum, 0.20 per cent molybdenum, and 0.35 per cent carbon; the endurance limit before nitriding was 76,000 lb. per sq. in. and after nitriding 85,000 lb. per sq. in. Two specimens were tested at 84,000 lb. per sq. in. to 225,000,000 revolutions without failure. Hengstenberg and Mailänder[279] and Sergeson and Clark[344] have also noted an increase in the endurance limit of steels after nitriding. The former have shown that slight surface imperfections have little or no effect on the endurance limit of nitrided steels as contrasted with those in the unnitrided condition. McAdam[334] stated that the corrosion fatigue of nitrided steel is superior to that of certain stainless iron.

161. Corrosion Resistance.—The reports of numerous investigators have shown that nitriding considerably improves the corrosion resistance of steel. The original rather extravagant statements, however, have been somewhat qualified through later work. Thus Sergeson and Deal[301] have reported that nitrided steel is adapted for use in acid solutions such as sulphuric and hydrochloric, that it is extremely resistant to alkali, atmosphere, crude oil, ethyl gasoline, natural gas combustion products, tap water and still salt water, that it is slightly attacked in aerated and in alternately wet and dry salt water, and that there seems to be no action between it and brass in either still or moving contact when immersed in hard water. Guillet and Ballay[243] also reported attacks by sulphuric and hydrochloric acids and a slight attack by oxygenated sea water and river water. Malcolm[250] noted that the nitrided steel resists quite satisfactorily the oxidation and corrosion effects of superheated steam, but cutting of nitrided valve seats by high-velocity wet steam is not unknown. Mochel* reported attack of nitrided Diesel-engine fuel-pump plungers handling high-sulphur fuel oil containing water.

In general, nitriding steel is best fitted for those applications involving wear with perhaps limited corrosive conditions and in

* Private communication.

which no great shock is involved. As a typical example, a shaft running in a hard bronze bearing might be considered, or one in which proper lubrication would be difficult. Its high hardness, together with absence of distortion, makes it adaptable to such tools as gages.

B. CHROMIUM MAGNET STEELS

It was Hadfield[19] who, in 1892, first noted that chromium additions to steel affected its magnetic properties. He found that iron-chromium alloys containing up to about 28 per cent chromium were strongly magnetic, and that with 40 per cent chromium they had lost most of this property and were magnetically weak. Hadfield's general observations were later confirmed by Treitschke and Tammann[42] who worked on alloys containing up to 90 per cent chromium. More recently, Fischer[276] reported on iron-chromium alloys containing 10 to 20 per cent chromium, noting that the maximum magnetic properties are found in those alloys containing 17.5 to 18.7 per cent chromium.

Curie[26] studied the effects of chromium on coercive force and residual induction, showing that these properties were both higher in a steel containing 2.5 to 3.5 per cent chromium with 0.5 to 0.8 per cent carbon than in plain carbon steels. Mars,[45] in 1909, recognizing the possibilities of these steels for use in magnets, compared their properties with those of the standard tungsten steels and found that a steel containing approximately 0.5 per cent carbon and 1.62 per cent chromium was particularly suitable for this purpose. Moir[59] has also described magnetic properties in chromium steels containing considerably more chromium.

Although Mathews[163] reported that chromium steel for magnets had been produced under his supervision as early as 1914, there is no doubt that the scarcity of tungsten during the World War and the interest centering about the discovery of substitutes for strategic materials such as tungsten stimulated the development and commercial production of magnet steels with chromium as the base alloy. At the present time this steel has largely supplanted the more expensive tungsten steel in commercial applications.

162. Composition of Chromium Magnet Steels.—The magnetic properties of chromium steels improve with increasing chromium content as illustrated in Figs. 151 to 154 from the work of Gumlich[109] and Stäblein.[261] This trend both with and without cobalt is also shown by Adams and Goeckler.[172] The larger proportion of the steels manufactured today, however,

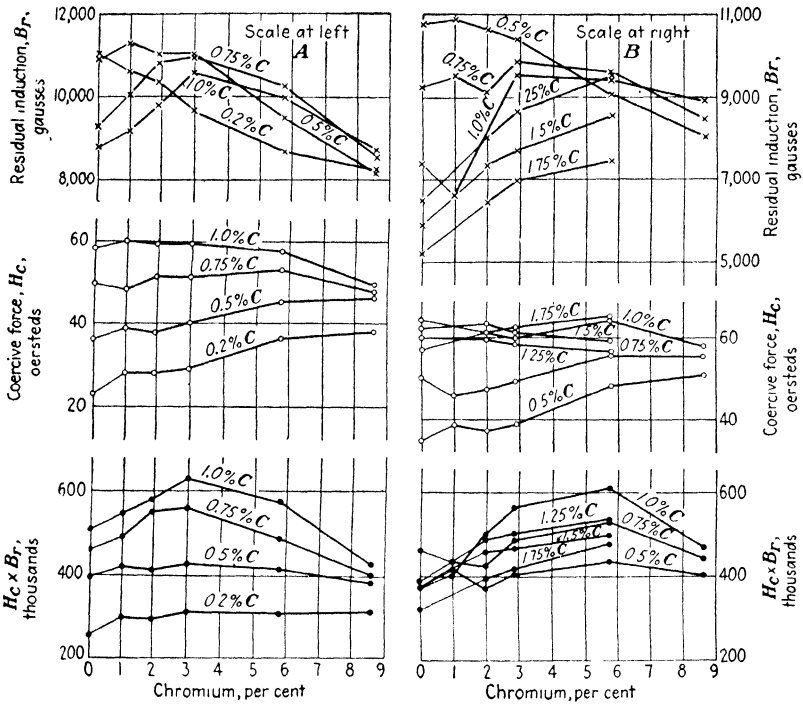


FIG. 151.—Effect of chromium on the magnetic properties of steels of increasing carbon content, *A*—after quenching from 850°C (1560°F.), *B* after quenching from 900°C. (1650°F.). (*Gumlich*[109])

averages about 2 per cent chromium with 1 per cent carbon, although in some steels the chromium may be as high as 4 per cent. This composition represents the economic balance between the cost and desirable magnetic qualities.

Recent work of Yensen and Ziegler[351] and others has shown the effects of impurities on the magnetic properties of steels, carbon being particularly noteworthy in this respect. The curves of Fig. 155 obtained by Hannack[140] illustrate the changes in magnetic properties with change in carbon content.

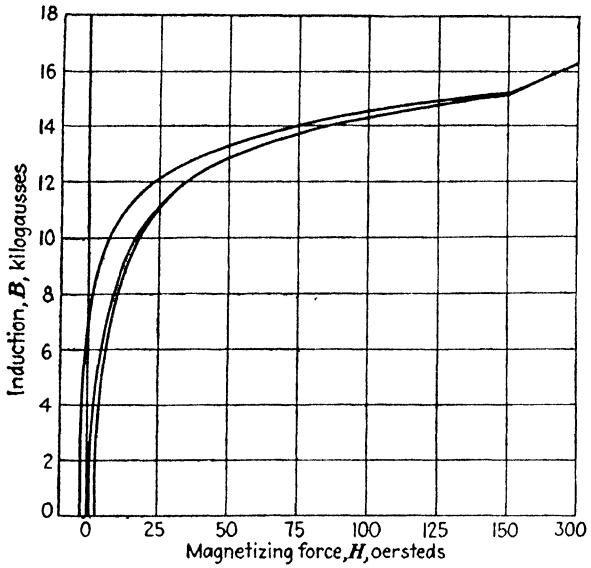


FIG. 152.—Magnetization curves of a steel containing 15.35 per cent chromium. (*Stablein* [261])

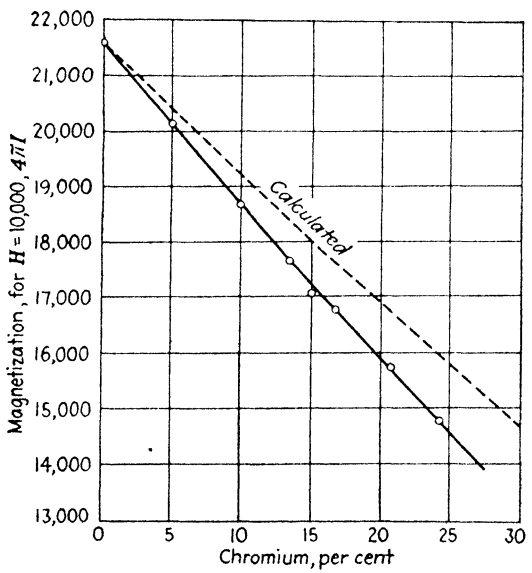


FIG. 153.—Effect of chromium on saturation values. (*Stablein.*[261])

The optimum results, it will be noted, are obtained at approximately 1 per cent carbon. The chromium content of these steels varied from 4 to 5 per cent.

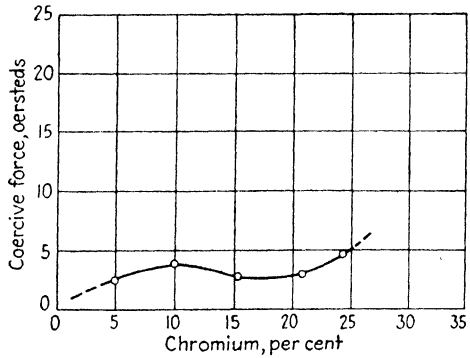


FIG. 154.—Effect of chromium on coercive force. (*Stablein.*[261])

163. Manufacturing and Prehardening Treatment.—Owing to the tendency toward carbide segregation, early practice called

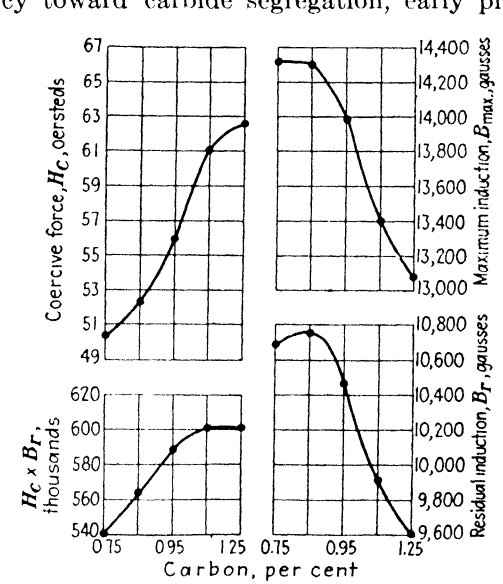


FIG. 155.—Effect of carbon on the magnetic properties of chromium magnet steels containing 4 to 5 per cent chromium. (*Hannack.*[140])

for the casting of magnet steel in small molds, but more recently large ingots have become common. The ingots are usually mill-cogged or rolled directly to billet form. The chromium steels

require considerable care in working and heat treatment, and in this respect are probably more susceptible to spoiling than those of the tungsten type. When possible, the material is given final heat treatment directly after rolling, as additional heat treatments generally have an adverse effect. A fully annealed bar usually shows after quenching such a loss in coercive force as to make it quite unsatisfactory for use. Any treatment that might involve heating for abnormally long periods, or very slow cooling, results in poor magnetic properties because of the fact that decomposition of the chromium carbides is likely to occur, or the carbide particles may be inclined to coagulate, making it

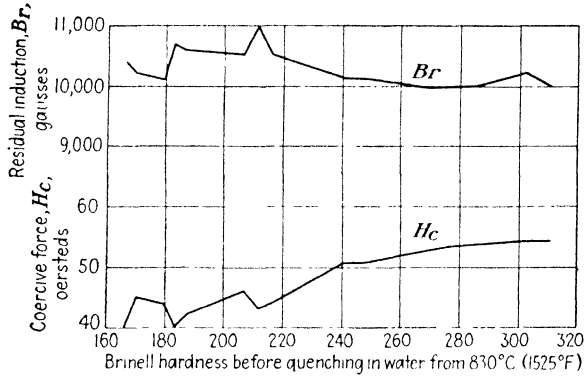


FIG. 156.—Relation between magnetic properties and Brinell hardness of a chromium magnet steel containing approximately 0.90 per cent carbon, 0.30 per cent manganese, 0.30 per cent silicon, and 2 per cent chromium (*DeVries* [154])

extremely difficult to bring them into solution by subsequent treatment.

When softening is necessary for machining operations, the material is heated for a minimum time only, to a point just below Ac_1. The hardness of the annealed steel varies from about 200 to 250 Brinell. The relationship of the Brinell hardness of chromium magnet steels before hardening to their final magnetic properties has been studied by DeVries;[153] his results are shown in Fig. 156.

164. Hardening.—Chromium magnet steels may be hardened by either water or oil quenching. Figures 157 and 158 from the work of Oberhoffer and Emicke[167] illustrate the effects of quenching temperature, time at temperature, and the quenching medium on the magnetic properties of a steel containing 1 per cent carbon

and 1.6 per cent chromium. Most magnet steels show a lower residual induction (B_r) and higher coercive force (H_c) after water than after oil quenching. It will also be noted that the length

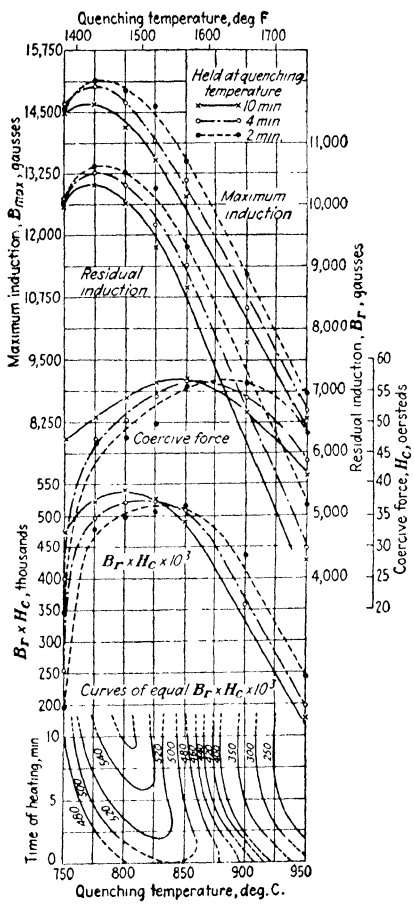


Fig. 157.

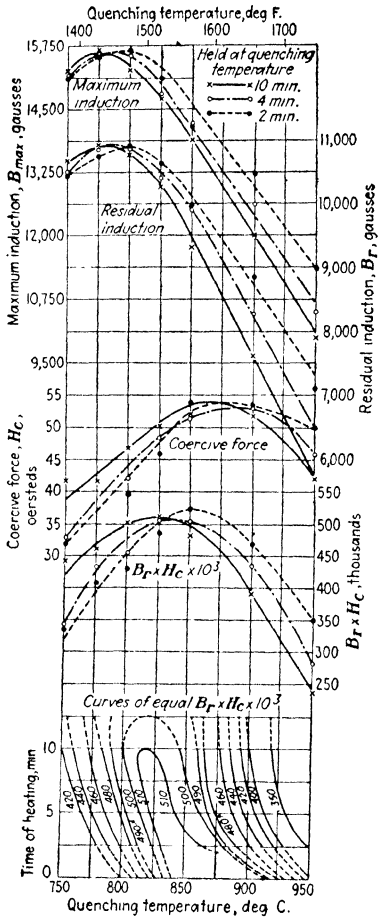


Fig. 158.

Fig. 157.—Effect of quenching temperature and time of holding on the magnetic properties of *oil*-quenched chromium magnet steel containing 1 per cent carbon and 1.6 per cent chromium. (*Oberhoffer and Emicke* [167])

Fig. 158.—Effect of quenching temperature and time of holding on the magnetic properties of *water*-quenched chromium magnet steel containing 1 per cent carbon and 1.6 per cent chromium. (*Oberhoffer and Emicke.*[167])

of time the specimen is held at temperature before quenching exerts an appreciable effect. A similar effect is noted when the quenching speed is varied.

It has been shown by Mathews[58,65,163,164] that quenching steels of the chromium magnet type in oil results in the retention of a greater quantity of austenite than when water is used, and that this results in a greater magnetic retentivity in the specimen so treated. This is clearly indicated in Fig. 159. The solid line represents the magnetic properties of the specimen as quenched,

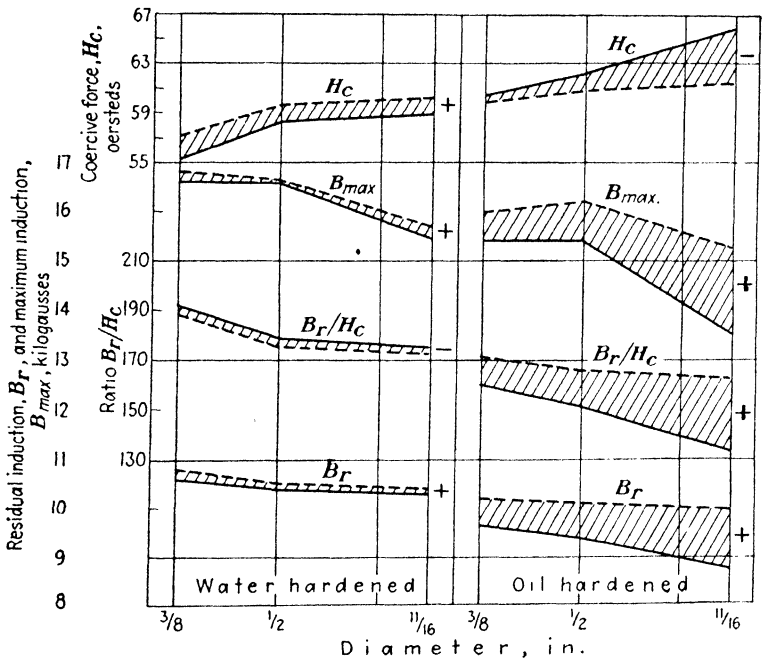


FIG. 159.—Effect of section size and of water quenching versus oil quenching on the magnetic properties of chromium steel, immersed in liquid air after quenching. The steel contained 0.81 per cent carbon and 2.91 per cent chromium. (*Mathews.*[163])

those after treatment in liquid air being shown by the dotted lines. The data in question were obtained on a steel containing 0.81 per cent carbon and 2.91 per cent chromium.

The choice of a correct hardening temperature is important and will, of course, depend on the composition of the material to be treated. This is evident from the work of Oberhoffer and Emicke mentioned before. In these investigations, as well as those of Schulz and Jenge,[189] the importance of the period for which the specimen is held at the hardening temperature before quenching is also shown. As indicated in the accompanying

Table 148, taken from their report, the latter investigators have found that for a steel containing 2 per cent chromium and 1 per cent carbon the maximum value for $B_r \times H_c$, the criterion of magnetic worth, was reached after a period of 10 min. treatment.

In tempering, magnets are never heated above 100°C. (210°F.). If this temperature is exceeded, there exists danger of partial decomposition of the martensite, with resultant loss in coercive force and residual induction.

TABLE 148.—EFFECT OF TIME AT HARDENING TEMPERATURE ON THE MAGNETIC PROPERTIES OF 1 PER CENT CARBON, 2 PER CENT CHROMIUM MAGNET STEEL*

Held at hardening temperature, min.	Residual induction, B_r, gausses	Coercive force, H_c, oersteds	$B_r \times H_c$, thousands
2	10,700	39 1	420
5	10,800	58 5	632
10	10,500	63 0	661
15	10,000	62 5	625
30	9,800	58 2	570

* Schulz and Jenge [189]

165. Aging.—Before being placed into service, all permanent magnets are aged. The purpose of this treatment is to stabilize as far as possible both the magnetic and microstructural properties of the steels, thus limiting the possibility of sudden changes while in use. This treatment may include subjection of the magnet to mechanical jarring, repeated quenching from boiling to ice water, allowing the magnets to stand for long periods, or magnetizing followed by partial demagnetization. The treatment varies with the manufacturer. Gumlich[109] has recommended the following:

1. Harden in tap water.
2. Magnetize after hardening
3. Demagnetize and temper at 100°C. (210°F.) for 10 hr.
4. Magnetize and quench ten times in ice water from boiling water, holding 5 min. at each temperature.

166. Chromium in Other Magnet Steels and Alloys.—The effects of the addition of chromium to steels of the tungsten type

result, according to Messkin and Kussmann,[370] in an improvement in magnetic properties. Steels of this general type have been described more or less fully in the volume of this series covering the alloys of iron and tungsten.[420] Parkin[146] reported an investigation on steel containing 6 per cent tungsten and 0.75 per cent chromium with carbon varying from 0.11 to 1.46 per cent. Mars[45] found very satisfactory properties in horseshoe magnets with 0.96 per cent tungsten, 1.23 per cent chromium, and 1.22 per cent carbon, while DeVries[153] quoted data obtained on a steel containing 0.96 per cent tungsten, 2.08 per cent chromium, and 0.85 per cent carbon.

Pakulla* has described methods of treating high-speed steels containing 4 to 5 per cent chromium, together with other elements, to produce good magnetic properties, while magnetic alloys containing chromium in varying amounts up to 5 per cent, together with other elements such as nickel, cobalt, iron, tungsten, molybdenum, and others, to be used in such applications as telephone apparatus or electric signaling systems, have been covered in other patent literature.†

C. HIGH-SPEED STEEL

Although some question exists whether chromium was present in the original high-carbon tungsten-manganese self-hardening steel as developed by Mushet in 1868 (see "The Alloys of Iron and Tungsten"[420]) it is certain that by 1880 this element was used as an addition agent to this type of steel. Chromium-tungsten steel, in which chromium had to a large extent replaced the manganese, was available before the famous work of Taylor and White, and it was largely with this steel that these investigators were concerned. Their invention did not involve a new alloy, but rather the heat treatment of an apparently standard article in a manner that was unique.

* E. Pakulla, U. S. Patent 1,661,907, Mar. 6, 1928.

† See: W. S. Smith, H J. Garnett, and J. A. Holden, British Patent 281,763, Sept. 8, 1926 (U. S. Patent 1,667,746, May 1, 1928, Canadian Patent 283,831, Oct. 9, 1928), and British Patent 295,443, May 13, 1927 (U. S. Patent 1,728,451, Sept. 17, 1929); C. P. Beath and B. J. Babbitt, U. S. Patent 1,743,309, Jan. 14, 1930; Deutsche Edelstahlwerke, A.-G., British Patent 356,169, Mar. 3, 1930; C. Sattler, U S. Patent 1,773,793, Aug. 26, 1930; and G. W. Elmen, U. S. Patent 1,792,483, Feb. 17, 1931.

Taylor and White, working with a steel containing 1.14 per cent carbon, 7.72 per cent tungsten, 1.83 per cent chromium, 0.18 per cent manganese, and 0.25 per cent silicon, found that by heating the tools to temperatures that were then thought sufficiently high to ruin completely any steel, considerable improvements were obtained. To quote one of the investigators[41] " . . . tools heated up to or above the high heat of 940°C. (1725°F.) proved better than any of those heated to the best previous temperature; namely, a bright cherry red . . . " They actually found that the closer the temperature of treatment approached the point of incipient fusion the higher were the cutting speeds at which the tools could be used.

The cutting demonstrations at the Paris Exposition, when the so-called high-speed steels were really introduced to the public, were made with steels of the chromium-tungsten type. Gregg[420] has given a full and interesting account of the development of high-speed steels from the old Mushet type to the analyses in use at the present time.

167. The Rôle of Chromium in High-speed Steel.—Three types of high-speed steel are now in more common use than others: the 18-4-1, containing 18 per cent tungsten, 4 per cent chromium, and 1 or more per cent vanadium; a second with 12 or 14 per cent tungsten, 4 per cent chromium, and 2 per cent vanadium; and a third, the 18-4-1 type with the addition of 4 to 12 per cent cobalt. Increased vanadium or cobalt is frequent in any of the three types. Further, 4 per cent chromium is common in molybdenum high-speed steel.

The unusual hardness of high-speed steel, originally thought to be due to the tungsten, is now known to be in a measure caused by the chromium content. The presence of chromium is responsible for the deep-hardening properties of the steel. According to Grossmann and Bain[322] the action of this element retards the breaking down of the martensite. They stated:

> This action is purely one of sluggishness of atomic motion and consequently chromium is an element contributing to its iron alloys a certain degree of high-temperature hardness. Thus a steel with about 17 per cent chromium and about 0.75 per cent carbon (very comparable in several ways to high-speed steel) will not be materially softened by tempering for an hour or more at 500°C. (930°F.) and if quenched to retain considerable austenite will show maximum secondary hardness

after this tempering. However, the maximum hardness which can thus be induced into such steel is about 10 points Rockwell lower than that of high-speed steel and inadequate for cutting purposes even though this hardness is actually maintained quite well at the temperature mentioned. Chromium then may be an auxiliary alloying element in a high-speed tool (not the principal one) and in this capacity it serves very well.

Edwards and Kikkawa,[62] who studied a series of steels in which the carbon and tungsten were constant, the chromium varying from nil to 6 per cent, have shown that the general effect of chromium is to increase the intensity of the hardening over that which tungsten alone imparts.[74]

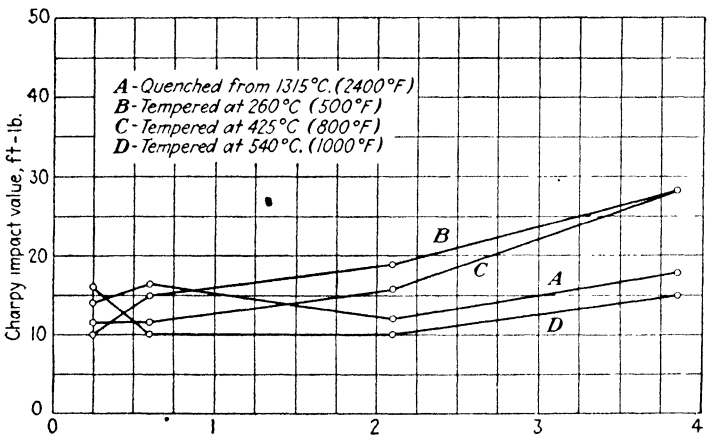


FIG. 160.—Effect of chromium on the impact resistance of high-speed steel. (*Bain and Grossmann.*[134])

The beneficial effect of chromium in high-speed steel is not limited to hardness alone. The toughness is to a considerable extent also a function of the chromium content. Figure 160, which is plotted from data reported by Bain and Grossmann,[134] shows the progressive improvement in this property with increasing chromium content as brought out by the Charpy impact test. The material used by Bain and Grossmann contained approximately 0.60 per cent carbon and 18 per cent tungsten. Above approximately 6 per cent chromium, the steel shows a tendency toward brittleness and grinding cracks.[364] This value may be said to be the safe maximum chromium content in these high-tungsten steels. Although this toughening

effect makes the steel more difficult to work, the advantages of a higher hot hardness in those steels containing about 4 per cent are invaluable. These steels maintain a high Brinell value even at temperatures up to 675°C. (1250°F.).

The improvement in cutting properties as a result of chromium addition has been reported by Edwards.[43] Figure 161, which is based on data calculated by Gregg,[420] illustrates this point.

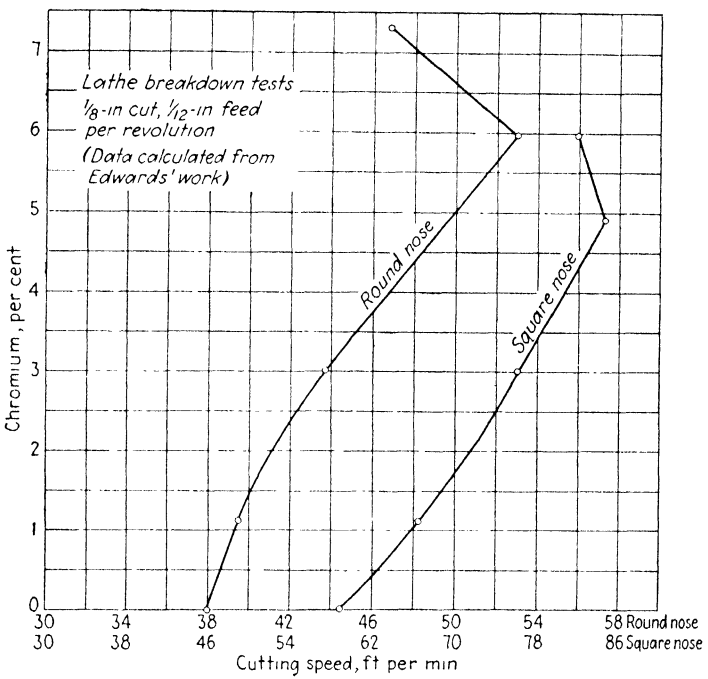


FIG. 161.—Lathe breakdown tests ($\frac{1}{8}$ in. cut, $\frac{1}{12}$ in. feed per revolution). Data calculated by Gregg[420] from Edwards'[43] determinations.

A rather extensive general discussion of the cutting properties of high-speed steels is given by Gregg in his monograph on "The Alloys of Iron and Tungsten."

Gill and Frost[179] reported that 4 per cent chromium is the optimum content for this element, as below this point the hardness is materially reduced, while above, brittleness is encountered which at 5 per cent is distinctly noticeable. Wagner[377] has reported that the tensile properties of high-speed steels are improved with the addition of chromium.

168. Effect of Chromium on Structure.—According to Bain and Grossmann,[134] chromium assists in preserving more austenite for the production of hard martensite when tempered at 595°C. (1100°F.), assisting also in diffusion in general so that more austenite is produced on quenching. The same investigators[322] stated that the smooth, slowly etching polyhedral grain structure of high-speed steel is revealed in ordinary microscopic practice because of the presence of chromium.

The effects of chromium in increasing the solubility of carbon and tungsten, and promoting uniformity of composition through the steel, are generally known.[179,322,470] In the chromium-cobalt high-speed steels, the same effect is found. The improvement of the properties of high-speed steel by cobalt is intensified by the action of chromium in increasing the solubility of cobalt.

D. ARMOR PLATE AND OTHER SPECIAL-PURPOSE CHROMIUM STEELS

The use of metal as a protective medium in warfare is old in the history of civilization. As early as A.D. 149, during the third Punic War, the Carthaginians are said to have protected a number of their vessels with wrought-iron plates in their battles with the Roman galleys. Throughout the Middle Ages the knights covered themselves with armor, and a number of incidents are reported in which ships have used metal plates as a means of protection during sieges or sea battles. It was, however, the successful results obtained by their floating batteries during the Crimean War that led the French to construct, in 1858, the first armored frigate, *La Gloire*. It is this occasion which may be said to mark the opening of the era of armored warships.

The manufacture of armaments is a highly specialized industry, and the technical developments in this industry have been published only to a very limited degree. A vast amount of data exists and in any given country armament manufacturers and their respective governments work in close contact. However, the metallurgical public at large learns little of the developments, so that a vast amount of information is very closely held. Because of this situation, the section on armor plate *per se* will be extremely brief and cursory in character and is included merely because chromium plays a prominent rôle in the industry. It

should be understood that the details from the literature are probably obsolete and that the authors have made no attempt either to judge these or to supply additional data. The full story of armor plate could well be written by a number of individuals, but it is probable that such a publication will be long delayed.

In the earlier days wrought iron was commonly used for protective plates, but with the development of the armored warship came the accompanying improvements in armor-plate composition, the last decade of the 19th century showing astonishingly great advances. From wrought iron the manufacturers passed rapidly through the era of the "sandwiched" plates consisting of teakwood set between two iron or steel plates; compound plates in which a hard and a soft layer were welded together; the use of nickel steel; the Harvey process of cementation of the plate face to produce a glass-hard surface with a comparatively tough back; and finally, the application of this cementation process, as further developed by Krupp, to chromium-nickel steels and chromium-molybdenum steels.[38,106]

169. Manufacture and Properties of Armor Plate.—The desired properties in steel for armor plate are very difficult to attain. Thus, armor plate must be hard enough to withstand the impact of the projectile and at the same time sufficiently tough to prevent shattering or cracking. In achieving this, chromium in combination with nickel, molybdenum, and other alloys plays a major rôle.

Although the compositions vary with different manufacturers, the following may be considered as approximate ranges for armor plate of various types:

Type of armor plate	Composition, per cent			
	C	Cr	Ni	Mo
Heavy	0 20 to 0 40	3 5		0 5
Heavy	0 30 to 0 40	1 5 to 2 25	3 5	
Medium	0 20 to 0 50	0 5	1 5	

Some steels for armor plate in which the chromium content has been increased to 5 per cent, usually accompanied by a

proportional reduction of the nickel, have been described in the patent literature. The 3.5 per cent chromium steel with 0.5 per cent molybdenum is also in this category. No applications of these alloys are reported as yet.

In casting armor-plate steel the ingot size chosen is considerably in excess of that required for the finished plate. Owing to the extremely heavy loss in cropping, which varies at times from 20 to 50 per cent, this is necessary to insure a sound product of high quality.

In connection with the comparative strength of the modern armor and of the older types of plate, Fig. 162 taken from the work of Ehrensberger[106] is of interest. The modern hard chromium-nickel steel shows a resistance to projectile impact three times as great as the original wrought iron.

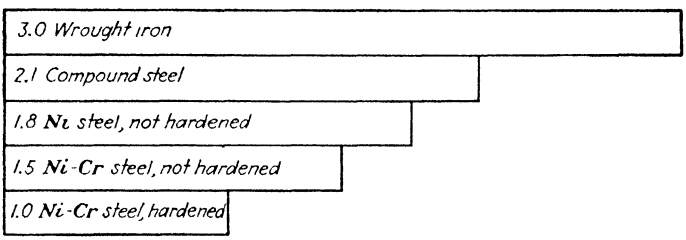


FIG. 162.—Relative thickness for equal resistance of the various kinds of armor plate. (*Ehrensberger.*[106])

170. High-pressure Chemical Steels.—Among the many requirements imposed upon the designers of chemical equipment, the correct choice of steel for use at high temperatures and pressures is particularly important. The synthesis of ammonia and the refining of oil represent typical industries making such demands, with the additional requirements, other than purely mechanical resistance to temperatures and pressure, of the resistance to attack by hydrogen or mixtures of hydrogen, nitrogen, and ammonia, under these more or less abnormal conditions.

It has been found that these gas mixtures under high pressures and temperatures cause the deterioration of many grades of steel. Vanick, de Sveshnikoff, and Thompson[208] gave micrographs of a plain carbon steel exposed to an atmosphere of hydrogen, nitrogen, and ammonia, in proportions closely approximating

equilibrium, at 500°C. (930°F.) and 100 atmospheres pressure for 4 months. Penetration of the gas was apparently entirely intergranular, resulting in fissuring or complete failure of the steel if exposed for a sufficient period of time. In earlier work, Vanick[130,150] showed that wrought iron, plain carbon steels, and many non-ferrous alloys are quite susceptible to this type of deterioration. He found that a chromium-vanadium steel containing 1 per cent chromium, 0.18 per cent vanadium, and 0.30 per cent carbon seemed, however, to possess considerable resistance.

TABLE 149.—COMPOSITION OF STEELS TESTED BY VANICK, DE SVESHNIKOFF, AND THOMPSON[208]

Serial No.	Composition, per cent						
	C	Mn	Si	S	P	Cr	V
Steels with increasing chromium							
1	0 37	0 39	0 27	0 022	0 017	0 04	0 19
2	0 29	0 53	0 16	0 011	0 015	0.51	0 28
3	0 30	0 68	0 26	0 024	0 012	0 93	0 18
4	0 31	0 48	0 12	0 011	0 011	2 01	0 34
5	0 33	0 37	0 26	0 013	0 028	7 70	0 18
6	0 42	0 35	0 06	0 009	0 025	14 40	0 18
27	0 25	0 40	0 60	0 020	0 020	13 50	
28	0 48	0 09	0 43	0 014	0 018	21 10	0 07
Steels with increasing vanadium							
7	0 40	0 53	0 18	0 013	0 018	1 05	0 02
8	0 37	0 52	0 20	0 018	0 018	1 05	0 07
9	0 35	0 37	0 20	0 013	0 020	1 02	0 14
10	0 37	0 55	0 18	0 019	0 018	1 07	0 31
11	0 27	0 34	0 29	0 011	0 025	1 24	0 65
Steels with increasing carbon							
12	0 16	0 55	0 34	0 023	0 023	1 03	0 20
13	0.58	0 68	0 23	0 017	0 011	0 73	0 18
14	1 16	0 55	0.20	0 018	0 022	1 06	0 20

Vanick, de Sveshnikoff, and Thompson[208] found that chromium is probably the best single addition element in preventing this type of attack. The results of their work on a number of

chromium-containing steels, analyses of which are given in Table 149, are graphically illustrated in Fig. 163, which presents the depth of deterioration as a function of the time of exposure of the materials to a mixture of hydrogen, nitrogen, and ammonia at 500°C. (930°F.), the mixture being close in composition to the theoretical equilibrium. For the best results the steel should

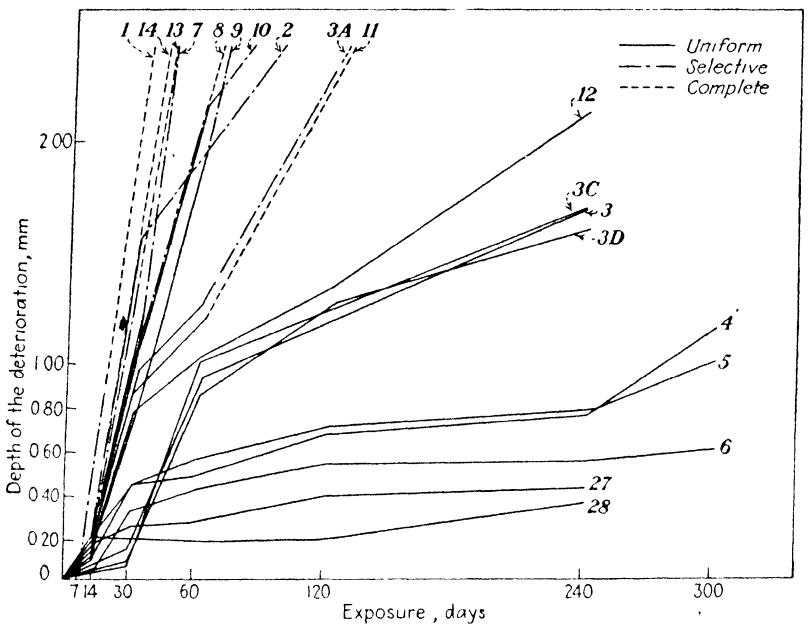


FIG. 163.—Rate of deterioration of carbon, chromium, and chromium-vanadium steels in a mixture of ammonia, nitrogen, and hydrogen. The analyses of the steels are given in Table 149. (*Vanick, de Sveshnikoff, and Thompson.*[208])

contain a minimum of 2.25 per cent chromium with no more than 0.30 per cent carbon.

Kosting[427] reported on the use of chromium-tungsten steels for high-pressure ammonia synthesis. Working at 600 atmospheres pressure and 300°C. (570°F.), a somewhat different set of conditions from that of earlier workers, he has, in general, verified the original findings of Vanick and his coworkers. The addition of 1 per cent chromium was found by him to be sufficient to make the steel resistant. His results also indicate that the addition of increasing quantities of tungsten up to about 2.85 per

cent brought about a progressive improvement which was enhanced by the further addition of chromium.

It has been stated by Saklatwalla[256] that chromium-nickel steels were formerly used abroad for the catalyst chambers in ammonia synthesis, but that more recently they have been replaced by the chromium-vanadium type. It is this steel which is being used almost exclusively in this country for this purpose, the average analysis according to Cox[383] being 0.30 per cent carbon, 2 per cent chromium, and 0.20 per cent vanadium. Mechanical properties of this steel are approximately 70,000 to 105,000 lb. per sq. in. tensile strength, 35,000 to 75,000 lb. per sq. in. yield strength, 25 to 20 per cent elongation in 2 in., and 44 to 40 per cent reduction in area.

TABLE 150.—PROPERTIES OF ALPHA-DELTA CARBURIZING STEELS*

Steel No	Alloy content, per cent					Tensile strength, lb./sq in	Yield strength, lb /sq in	Elongation in 2 in., per cent	Reduction of area, per cent	Rockwell *C* hardness of case of oil-quenched 1-in. rounds
	Si	Cr	V	W	Zr					
1	2 31	1 04				53,000	77,000	28	62	62
2	1 55	1 21			0 40	32,000	63,000	35	71	62
3	1 31	0 84	0 26			58,000	86,000	32	65	65
5	2 08	1 21	0 13			51,000	83,000	29	64	64
6	1 47	1 27	0 19			40,000	81,000	28	46	60
7	2 04		0 67			35,000	58,000	35	74	62
8	1 05		0 47			50,000	66,000	38	78	62
9	1 45	1 27	0 14		0 23	35,000	67,000	36	68	61
10	1 52	0 62		1 45		43,000	91,000	23	35	62
11	1 84									65

* Kinzel.[331]

171. Ferritic Carburizing Steels.—The problem of distortion in the hardening of carburized materials, which is usually caused by differential volume changes through the mass, has been the subject of much research. Among the more practical of the solutions has been the development of so-called alpha-delta carburizing steels by Kinzel.[331] These steels contain one or more of the alpha-forming constituents such as chromium, vanadium, silicon, and others. Thus, with a low carbon content the gamma loop is suppressed, with the resulting absence in the core of transformation points. Carbon is not readily absorbed

by ferrite. The latter constituent, however, does take it up in sufficient quantity to bring about the change to austenite which possesses much greater absorbing power, and it in turn transmits the carbon to the adjacent ferrite, and the process continues at rates similar to those obtained in the normal carburizing steels.

The core properties of these ferritic steels are satisfactory as may be seen from Table 150. Although the strength is somewhat lower than might be expected in normal carburizing steels, it is sufficient for many commercial applications in which lack of distortion is a desirable property.

In measuring distortion, long slender bars and disks with eccentric holes and slots were used. Within the limits of accuracy of the instrument used, 0.0005 in., no distortion could be found in the slotted disks, and the bars showed deviations from straightness less than one-tenth of those found in bars of plain carbon steel with a core containing 0.15 per cent carbon.

E. AUTHORS' SUMMARY

1. Chromium is used in the special-purpose steels discussed in this chapter because of some specific effects which may or may not be a modification or intensification of the phenomena discussed in the earlier chapters on principles. In the nitriding steels, advantage is taken of the hardening and the carbide-forming effect to a moderate degree in the same way as in the usual engineering steels, but the ability of chromium to form relatively stable nitrides is an additional effect not previously discussed. This stability of the chromium nitrides plays a still more important rôle in steels containing much higher concentrations of chromium; this is treated in the second volume. Because of the combination of desirable properties imparted by chromium together with its nitride-forming tendency, it is a common element in nitriding steels. The economics of its use are such that it will probably maintain its position in these steels for some time to come and will continue to be used in connection with aluminum, vanadium, or molybdenum for producing nitriding steels having optimum manufacturing characteristics and physical properties.

2. In magnet steels, again the phenomena of deep hardening and fine-carbide formation play a rôle similar to that of chromium in tool steel, but a further specific effect seems to be evident, as

similar magnetic properties are not readily obtained by the use of other deep-hardening carbide-forming elements. While other types of steel, such as high-cobalt, high-tungsten, and the like, give improved magnetic characteristics where permanent magnetism is involved, the economics of the chromium magnet steels are such that they will probably continue to fill a definite engineering need.

3. Chromium in armor plate is a good illustration of the accentuated effect of the depth-hardening phenomenon often referred to in the previous chapters. The combination of this depth-hardening effect with the beneficial effect of chromium in the carburizing process and the tendency to resist decarburization result in a universal application of chromium in armor plate.

4. The use of chromium in autoclaves, pressure forgings, and the like is again due to its effect on depth hardening and carbide dispersion, but here another specific effect plays an important rôle, namely, the tendency to resist decarburization produced by other than oxygen-bearing gases such as molecular and atomic hydrogen, in addition to the previously discussed resistance to decarburization in atmospheres containing carbon dioxide, water vapor, and the like. While it is probable that this specific property is also contributed by other strong carbide-forming elements, the combination of this property with the depth-hardening characteristic as well as the economics of the chromium-containing steels would seem to indicate that chromium is an important element in steels for such applications.

5. The alpha-forming tendency of chromium, together with the fact that reasonably large quantities may be used in steel without producing primary or secondary compound formation, as in the case of silicon—another strong, low-cost, alpha-forming element —makes chromium desirable when alloy combinations intended to suppress the gamma transformation are desired. The suppression of the gamma phase seems to be essential for optimum non-deforming properties of carburized steel and the choice of chromium in this connection is further emphasized by its favorable effect on the carburizing process. The so-called alpha-delta non-deforming carburizing steels containing chromium are relatively new, and their application as yet is limited in scope. The principle, however, is sound and may be applied where elimination of deformation is an all-desirable feature.

CHAPTER XII

LOW-CHROMIUM CAST IRON

Manufacture of Low-chromium Cast Iron—Structure of Low-chromium Cast Iron—Properties of Low-chromium Cast Iron—Effect of Low Chromium Additions on Heat Resistance and High-temperature Strength—Miscellaneous Data on Low-chromium Cast Iron—Authors' Summary

The character and properties of cast iron are affected by very small additions of chromium. The specific characteristics so imparted are of such importance as to require a detailed description of the method of production and the resultant properties of these low-chromium irons. As low-chromium cast irons can be produced economically, the use of these irons in the last 10 years has become widespread, and they may well be listed among our important engineering materials. In addition to a detailed discussion of the effect of chromium on the properties and structure of plain cast irons, brief mention is also made in the present chapter of the effect of chromium on cast irons containing other alloying elements.

It is difficult to trace directly the effect of low chromium additions on cast iron by reference to the iron-carbon or iron-carbon-chromium diagrams, as cast iron usually contains at least 1 per cent or more silicon, which definitely alters the equilibrium conditions of the system. Also, it has been found that the effects of section size and cooling rate change the equilibrium conditions[333] in cast irons to such an extent as to render empirical results of greater value in the light of our present knowledge than theoretical considerations.

A. MANUFACTURE OF LOW-CHROMIUM CAST IRON

It is generally recognized that cast iron is highly complex and that this complexity involves not only distribution of phosphides and the like but also the distribution of the carbon between graphite and cementite and the physical nature of the graphite and cementite particles. The matter is further complicated by

the distribution of elements other than iron between some form of cementite and solid solution in the ferrite proper. In order to understand clearly the rôle of any given alloying element, it would be necessary to show, first, its effect on the distribution of the carbon and on the nature of the graphite flakes, nodules, or other particles; second, its effect on the cementite in changing its composition, particle size, and distribution; and third, the proportions of the added alloying element entering into the cementite and going into solution in the ferrite, together with the effect of the alloying element when present as the solute. Unfortunately, these various effects are so intimately allied and dependent on each other that precise pertinent data are lacking for most alloys, and chromium is no exception. Certain qualitative effects may, however, be gathered from the existing data, and the subsequent presentation has been made with the view of emphasizing such qualitative effects wherever possible.

Actual examination of many castings has shown definitely that a small addition of chromium tends to produce the pearlitic condition in a gray cast iron and to eliminate patches of free ferrite. In other words, its presence permits the production of a uniformly pearlitic cast iron with greater variation in section size and cooling rate. The pearlite so formed in the low-chromium cast iron tends to be more stable on exposure to heat or on subsequent thermal treatment of the castings, probably owing to the tendency of chromium to form carbides. In some instances percentages as low as 0.10 per cent chromium have been found to exert a definite influence. In percentages up to approximately 0.5 per cent, or occasionally somewhat higher, depending on the silicon content of the iron and its section, the effect of chromium is chiefly evident in this pearlite formation. As chromium is increased above this range and up to 3.5 per cent, free cementite makes its appearance and progressively increases with chromium content until, with the higher percentages of chromium, the iron may possess a completely white fracture with graphite largely suppressed. Most of the specific properties of low-chromium cast irons are directly related to its effect on the carbides.

172. Melting Practice.—Chromium cast irons are generally made either in a cupola, air furnace, or electric furnace. Because of the lower cost of melting, the greatest tonnage is at present produced in the cupola. No difficulty is experienced in the addi-

tion of chromium to an electric-furnace melt, and the chromium recovery—80 to 95 per cent—is approximately the same as in steel-making practice. Chromium is incorporated in cupola melts by three different methods. In the first, now generally abandoned in favor of the next method mentioned, alloys high in chromium, such as ferrochromium, are added directly to the charge in lump form. The second method involves the addition to the charge of cement briquettes, each containing a definite amount of ferrochromium, and the third method involves a ladle addition of ferrochromium or a similar alloy high in chromium content.

As indicated, ferrochromium is almost universally used to add chromium to cast iron. This ferrochromium generally contains 4 to 6 per cent carbon and 65 to 70 per cent chromium, the remainder being largely iron. As noted in Chapter I (page 21), special low-melting alloys are available which may be used to add chromium to cast iron. In a limited number of cases, other alloy combinations have been employed when it is desired to introduce other alloying elements together with chromium, and appreciable tonnages are made using low-alloy iron in the base charges. This iron generally contains about 2 per cent chromium and 1 per cent nickel.

When introducing chromium direct to the charge in lump form, it is well to have most of the ferrochromium or other chromium-bearing alloy in sizable pieces to prevent sifting and excessive oxidation. In lump form, ferrochromium is mixed throughout the charge. Chromium recoveries approximating 80 per cent are reported[283] for this method of addition, although this recovery varies widely with varying methods of cupola operation. In general, this method of addition is not recommended, having been superseded by the briquette method. Chromium additions as protected briquettes are common. The briquettes contain a predetermined amount of chromium, usually 2 lb., as ferrochromium briquetted with a cement binder. The briquettes are placed on top of the coke and below the remainder of the charge. In this position they become surrounded by the charge as the coke bed burns out, and better alloying with the charge is secured. The cement binder protects the chromium from excessive oxidation until the melting zone is reached. The chromium recovery from briquettes varies from 90 to 98 per cent. With usual

cupola conditions, 96 per cent recovery is common.[396] The third method is to add chromium to the ladle. Ferrochromium, crushed to go through 12 to 24 mesh, is most readily dissolved in the molten iron. The chromium recoveries with this method of addition vary upwards from 70 per cent. If the alloy addition is made to the stream during the filling of the ladle, better than 90 per cent recovery is common. Additions up to 1 per cent chromium may be made in this way without dangerously chilling the molten iron. Reladling is sometimes employed to get better chromium distribution in the melt. This is automatic when briquettes are used and, in general, the briquette method results in more uniform analysis.

173. Casting Properties.—The effect of low chromium additions on the fluidity of cast iron is found to be of minor importance when the analysis and section of a casting are such as to produce gray iron. Extensive tests on cupola cast irons containing from 0 to 0.9 per cent chromium, which were cast into transverse bars, fittings, 2-in. elbows, and plates, showed no appreciable difference in fluidity.[356] Wickenden and Vanick,[171] in working with nickel-chromium cast irons, reported no observable difference in fluidity with chromium content up to the maximum of 0.50 per cent employed, and this seems to hold true even up to 1.5 per cent chromium. In regard to shrinkage, a similar condition exists: if the chromium content is adjusted so that the final casting is gray, the shrinkage is not noticeably affected. In fact, some decrease of shrinkage may be produced in high-silicon iron by the counteracting effect of chromium. However, as the chromium content is increased above the amount necessary to produce a pearlitic iron, the shrinkage progressively increases as the iron tends to become white in structure.

The general effect of chromium, as reported by all investigators in this field, is to reduce the size of the graphite plates. This is frequently reported as "increasing the density and refining the grain of cast iron." Little direct information on the influence of chromium on porosity is available. Assuming proper mold design with ample gates and risers, porosity may be considered as depending on the volume change on solidification. The volume change is such that no normal gray cast iron is porous in the ordinary sense of the word, and the addition of chromium or any other alloying element does not bring about any important

difference in volume change until graphitization is materially suppressed.

Low-chromium cast irons have been cast in both green and dry sand molds with satisfactory results.

B. STRUCTURE OF LOW-CHROMIUM CAST IRON

Cast iron may be considered as a matrix having many of the characteristics of steel plus excess carbon as either graphite or cementite. The form of this additional carbon in plain cast iron is controlled by the cooling rate (section of casting) and the silicon and carbon contents of the iron. Other factors such as degree of oxidation may exert a secondary influence. The structure of the cast-iron groundmass also varies depending on these same factors. The properties of a particular cast iron depend directly on the structure of the groundmass and the form in which the additional carbon is present. An alloying agent must affect one or both of these structural constituents to have a marked effect on the nature or quality of cast iron. Chromium has been found to affect both.

174. Effect of Chromium on the Groundmass.—The effect of chromium on the groundmass of cast iron is definitely related to the cooling rate and, therefore, to the section. Moreover, the graphitizing action of silicon and the carbide-forming action of chromium are in definite contradiction. The relative amounts of silicon and chromium are the determining factor for a given mass rather than the chromium content *per se*. This thought should be kept in mind in the following report of the experimental work by the various investigators. It was early established that chromium, even in amounts under 0.5 per cent, definitely increases the combined-carbon content of cast iron.[72,160,182,240,245,281,283,356,379,401] It has been fairly well established that this action arises from the fact that chromium forms a stable double or mixed carbide with iron.[240,283] Arnold and Read[51] designated this carbide $Fe_3C{\cdot}Cr_2C_3$, the relative proportions of the iron carbide and the chromium carbide varying with the chromium content. Westgren, Phragmén, and Negresco[236] presented X-ray evidence that chromium enters the carbide in the form of a solid solution, a chromium atom replacing an iron atom, giving the general formula $(FeCr)_3C$. Working with high-carbon tool steel, these

investigators found that as much as nine-tenths of the chromium added may so combine with the carbide.

Additions of chromium from 0.10 to 0.75 per cent, the exact amount depending on the analysis of the iron and its section, were found to render the groundmass of a gray cast iron completely pearlitic;[262,356,477] apparently chromium also has a tendency to produce fine pearlite. A noticeable decrease in the size of graphite flakes or a "refining of the grain" has been also reported. The pearlite-forming effect is most noticeable in cast iron containing 1.75 per cent or more silicon. Such irons in all but very thin sections often possess a relatively weak groundmass owing to the presence of an appreciable amount of free ferrite. This groundmass may be strengthened by the addition of 0.25 to 0.75 per cent chromium.[241] With heavy cast sections this effect of chromium is even more important, and the amount of chromium necessary to preserve a fine-grained and pearlitic structure increases up to almost 1 per cent as the section becomes heavier.

In unalloyed pearlitic irons low in silicon, chromium additions exert a distinct refining action on the pearlite, but the amount of chromium added usually should not exceed 0.50 per cent.[240] In such low-silicon castings where very thin walls exist, chromium may be limited to 0.25 per cent to avoid the formation of excessive free cementite and consequent decrease in machinability. Under such conditions, greater latitude in chromium additions is rendered possible by a slight increase in silicon content or other graphitizing agent.

Experiments[356] have shown that variation of chromium from 0.25 to 0.75 per cent in cast irons containing 1.75 per cent silicon or more does not produce excess cementite and concomitant machining difficulties when the composition is adjusted for section size. This is due to the fact that a relatively small chromium addition such as 0.25 per cent renders the iron largely pearlitic after which further additions of chromium, for example up to 0.75 per cent, serve to produce a pearlitic structure under limited cooling conditions without production of excess cementite. The combined carbon rapidly rises to about 0.60 per cent and then does not increase above approximately 0.90 per cent.[477] In one set of experiments[356] additions of up to 0.79 per cent chromium were made to cupola cast irons containing approximately 2.90 per

cent carbon and 2.50 per cent silicon. Figure 164 illustrates the structure of such irons containing 0.01, 0.48, and 0.79 per cent chromium, cast in telescope bars varying from ¾ in. to 2½ in. in diameter as well as in sections 6½ in. in diameter. A fine pearlitic structure was maintained in the chromium-treated 6½-in. section. It has been observed[401] that small amounts of chromium apparently emphasize the phosphide eutectic on etching, possibly indicating that the first cementite that forms tends to occur with the phosphide. It has also been found that with properly selected chromium additions the depth of chill of a given iron can be materially increased while retaining a relatively shock-resistant pearlitic core.

175. Effect of Chromium on Graphite Formation.—As noted before, a number of investigators have found that small chromium additions produce finer graphite flakes in gray iron, particularly if the cast iron normally tends to form large graphite flakes either because of its analysis or casting section. One of the most important observations[356] is that the chromium also produces a more uniform distribution of graphite, thus tending to prevent the formation of ferrite areas accompanying large graphite flakes. This action of chromium is illustrated in Fig. 164.

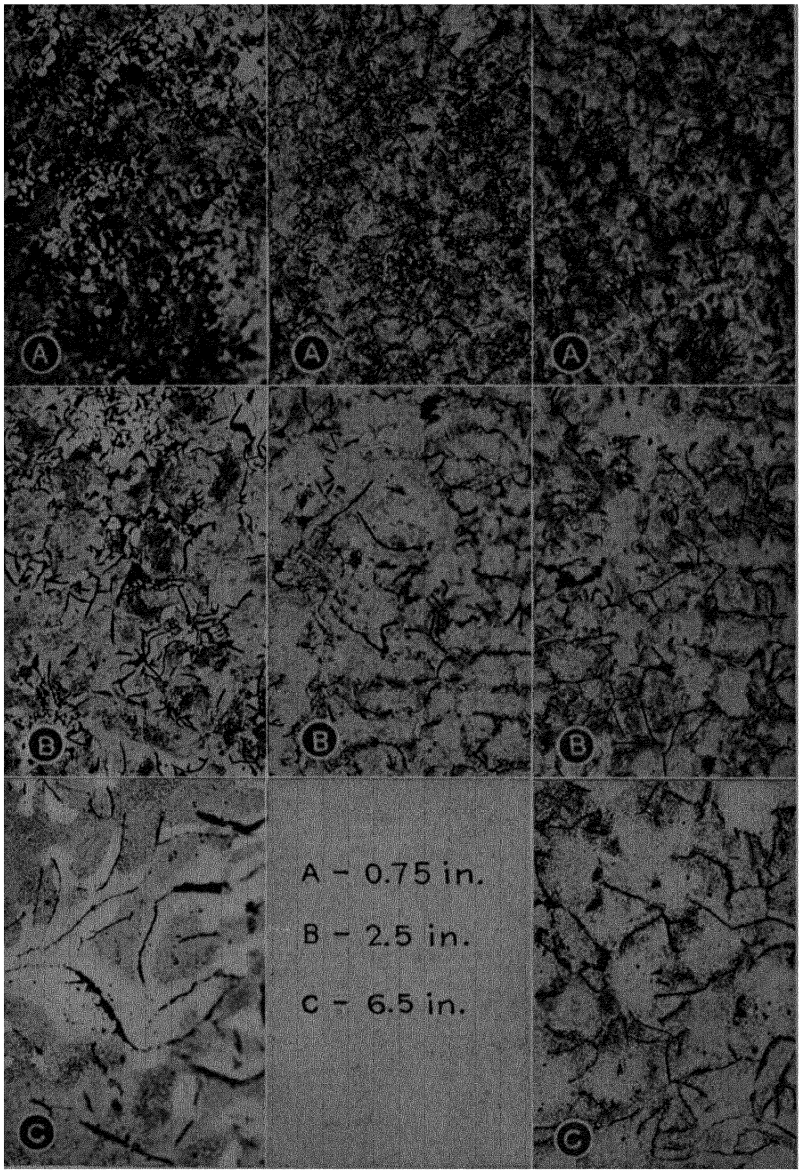
TABLE 151.—APPROXIMATE EFFECT OF CHROMIUM ON THE STRUCTURE OF 1-IN. ROUND BARS OF A SOFT CAST IRON*

Chromium,† per cent	Structure
0	Ferrite and coarse graphite.
0.30	Less ferrite and finer graphite and pearlite.
0.60	Fine graphite and pearlite
1.00	Fine graphite and pearlite and small carbides.
3.00	Graphite disappears.
5.00	Much massive carbide
10.00 to 30.00	Fine carbides

* Symposium on Cast Iron.[379]

† Silicon and total carbon percentages not given in the original paper

As the chromium content of cast iron is increased above the optimum for the production of pearlitic iron, the amount of graphite is progressively decreased until, with 3 per cent or more chromium, the graphite formation may be entirely suppressed, being replaced by needles and areas of massive cementite. Table 151, from the "Symposium on Cast Iron,"[379] summarizes the approximate effect of chromium on a cast iron of usual



0.01 % Cr 0.48 % Cr 0.79 % Cr

FIG. 164.—Effect of small chromium additions on the structure of cast iron containing 2.80 to 2.95 per cent total carbon, 0.46 to 0.57 per cent combined carbon, 2.52 to 2.57 per cent silicon, 0.77 to 0.80 per cent manganese, 0.092 per cent sulphur, and 0.240 per cent phosphorus. (*Burgess.*[356])

analysis, cast in 1-in. round bars. That similar structures can be obtained in unalloyed low-silicon iron is generally known. The disadvantages of such procedure are many, and the reader is referred to section 187 for further discussion of this matter.

C. PROPERTIES OF LOW-CHROMIUM CAST IRON

176. Hardness.—Small additions of chromium act to increase the hardness when iron is cast in standard arbitration bars, 1.20 in.

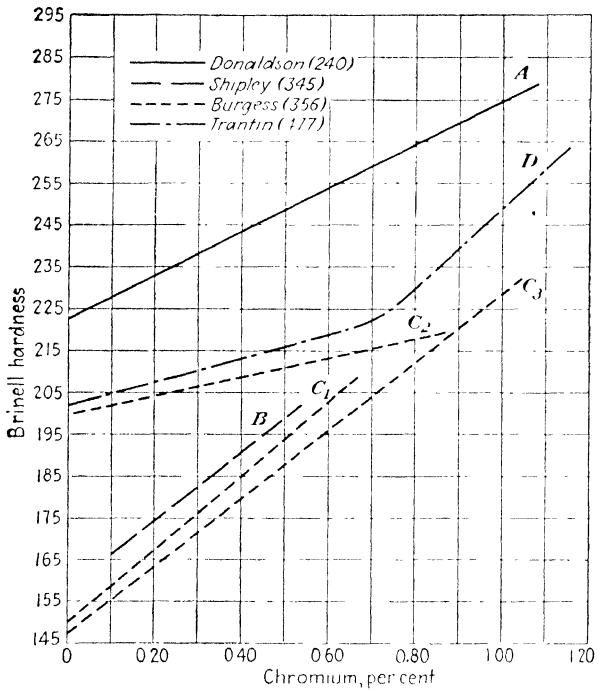


FIG. 165.—Effect of increasing chromium content on the hardness of cast iron.

in diameter. The change in hardness with chromium content in such castings, as found by four investigators,[240,345,356,477] is illustrated in Fig. 165. The curves are based on six cast irons of appreciably different analyses and initial hardness, but it is evident that, given a cast iron with a base hardness of 145 to 165 Brinell, the addition of chromium increases the hardness progressively until with 0.50 per cent chromium it is about 190 to 200 Brinell. In these irons the average increase in hardness is approximately 8 to 10 Brinell units for each 0.10 per cent

chromium. When the cast iron has an original hardness of 200 Brinell or greater, the relative increase in hardness with small chromium additions is much less marked, a Brinell increase of only 10 to 27 units being effected by chromium additions up to 0.50 per cent. This is in accordance with the previously noted fact that once a pearlitic structure is stabilized in the iron, a range exists in which further chromium additions usually serve

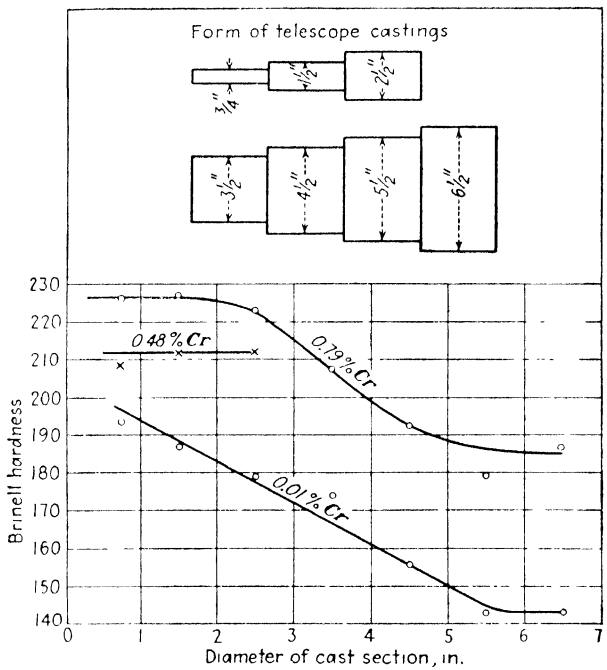


FIG. 166.—Effect of chromium on hardness for increasing section size. (*Burgess.*[356])

to refine the pearlite without production of any significant amount of free cementite.

The hardness and the pearlitic structure of cast iron can be maintained in heavy sections by low chromium additions. Specific information on this point is found in a diagram[356] of the hardness values obtained on the telescope castings described in the previous section on structure. A graph of the hardness of sections varying from ¾ to 6½ in. is shown in Fig. 166. In this case 0.48 per cent chromium was sufficient to prevent softening on such an increase in casting section. In a section 6½ in. in

diameter, 0.79 per cent chromium maintained a hardness of 180 as compared to a drop to 143 Brinell in the instance of the same base iron to which no chromium had been added.

Although no quantitative data are available, hardness increase owing to a given amount of chromium in an iron is more than proportionate as the size decreases to very thin sections and the corresponding rate of cooling increases.

When the chromium content is increased above a certain critical percentage, depending on the analysis and size of the casting but usually over 1 per cent, a rapid rise in hardness is evident. This corresponds to the appearance of large quantities of massive cementite in the structure. When the structure has been rendered completely white by chromium additions, the hardness increases slowly with further chromium additions.

As noted before, the chilling tendency or depth of hardening of cast iron can be controlled within limits by low chromium additions balanced against the silicon content. The use of chill tests is common together with a minor final addition of ferrosilicon or ferrochromium, the alloy and amount added being based on the result of the chill test.

177. Machinability.—Consideration of the machinability of low-chromium cast irons or any cast iron should involve a definition of what constitutes a readily machinable cast iron. Unfortunately, opinions differ widely on this point, but in recent times high-test plain and alloy irons, of 228 or even 240 Brinell hardness, are commonly produced and machined. Small-scale machining tests on irons containing 2.50 per cent silicon have been reported[356] as failing to show any major variation between the machinability of a plain cast iron and of one containing 0.79 per cent chromium. Piwowarsky and other investigators have stated that additions of up to 0.50 per cent chromium have been made without adversely affecting machinability in approximately 1-in. round sections. Donaldson,[240] using a base iron with the high original hardness of 223 Brinell and a silicon content of slightly under 1.5 per cent, reported no change in machinability of standard transverse bars with 0.4 per cent chromium addition, but with an 0.66 per cent chromium addition difficulty in machining was encountered. There is no doubt that chromium, as well as any other alloying agent, must be used in quantities determined by the nature of the cast iron to which it is added and the

section into which the iron is to be cast. In general, the higher the original hardness of the iron above a certain base hardness, such as 200 Brinell, the lower the allowable chromium content before serious variation in machinability will be noted. This is of significance in dealing with base irons that already have a structure containing localized free cementite patches and may explain the difference between the results obtained by Burgess[356] and by Donaldson. In the opinion of many, Burgess' 0.79 per cent chromium is too high for a ¾-in. round section under average conditions, or for production in machine-shop practice.

It is of interest here to note that, operating with a constant base iron and constant section, the hardness of a cast iron has been progressively increased by chromium additions alone to 285 Brinell,[356] the iron still being machinable under the conditions in question. Hamasumi[158] reported good machinability in an iron containing 1.62 per cent silicon and 0.90 per cent chromium, with a hardness of 252 Brinell. Similar observations of retention of machinability by alloy steels and cast irons up to high hardness values have been made by many investigators when the increased hardness has been produced solely by alloy additions. However, such results must be applied with caution as a change in the base iron or in the section may require a major adjustment of composition for satisfactory results, and the investigator may have had a very different concept of machinability from that of the production superintendent.

It is evident from a survey of the existing information that, if a cast iron of high hardness is desired, a superior and more dependable product will be obtained if the silicon is held to a value insuring a gray-iron structure and the hardening tendency of the iron is controlled by increasing chromium additions. Obviously, however, if a readily machinable gray iron is desired, the chromium-silicon ratio should be so controlled as to prevent the formation of iron containing an excessive amount of massive cementite as such irons are no longer commercially machinable.

In summarizing this discussion on machinability, the extremely controversial nature of this subject is to be particularly noted. Irons considered machinable with a simple lathe might well be considered non-machinable in an industrial application involving automatic equipment. Any increase in hardness tends to render the iron less satisfactory from a machining standpoint, as does

any decrease in size of the graphite flake, or increase in toughness. Moreover, in many machining operations the hardness of the cast-iron section as usually machined may not be a criterion of machinability. The nature of the skin on the casting when light cuts are used may far outweigh the inherent structure of the iron proper. The presence of fins due to parting surfaces, when such fins have become increasingly hard owing to the presence of chromium or any other alloying agent, may completely change the aspect of the iron from the standpoint of machinability and this may also be the case where sharp corners are involved. Thus, no broad conclusions on the machinability of alloy irons are warranted. In the case of the chromium irons, we may, however, attempt the generalization that any chromium addition tends to make the irons less readily machinable, that in a well-balanced iron the effect is not of a major order, and that such well-balanced chromium irons are being regularly produced and commercially machined.

178. Strength Properties.—It has been demonstrated[72,238,240,271,283,356] that additions of chromium up to 1 per cent increase the transverse and tensile strengths of gray cast iron. This increase has been traced by many investigators and found to vary from approximately 5 per cent to over 30 per cent. The degree of increase in strength is again based on suiting the chromium addition to the character of the base iron. In general, the greatest comparative increase in strength of cast irons in transverse-test bars results from additions of up to 0.5 per cent chromium. In heavier sections higher chromium additions (up to 1 per cent) are more effective.

In a diagram for cast iron of the type proposed by Maurer[144] the completely pearlitic composition range is considerably extended by low chromium additions, particularly in the higher silicon and carbon ranges. Coyle[271] has plotted an approximate Maurer diagram for cast irons containing 0.50 to 0.75 per cent chromium in which an area is added showing a range of compositions giving maximum strength (Fig. 167). Even though the chromium content was not altered to suit the requirements of the irons, especially in the lower silicon and carbon ranges, the size of this area where tensile strengths of 40,000 to 45,000 lb. per sq. in. can be obtained was increased to over 2½ times that shown for plain iron. With proper modification of chromium

content in the lower silicon and carbon ranges, and increase of chromium content in the higher silicon and carbon irons, the range of compositions where maximum strength is obtainable would be further extended.

Figure 168 shows the transverse strength of standard A.S.T.M. bars plotted against chromium content in the case of four different types of irons.[345,356] Curves *A* and *B* are for cupola heats containing comparatively high and low carbon contents respectively, and *C* represents a lower grade iron, poorer because of special cupola conditions. Curve *D* is a base cast iron possessing a constant nickel content of approximately 0.50 per cent in

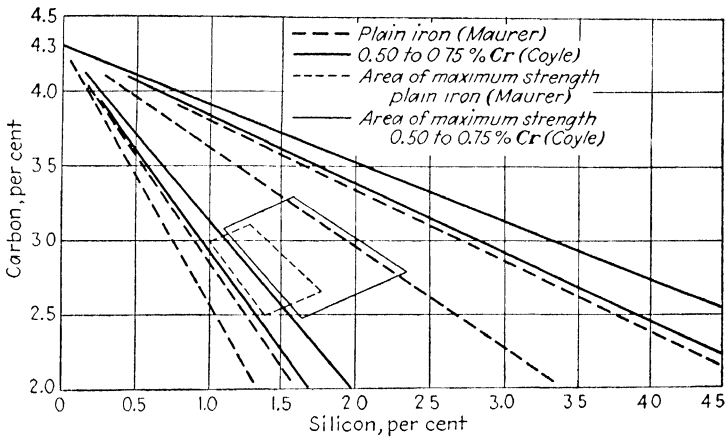


FIG. 167.—Effect of chromium on the Maurer constitutional and strength diagram of cast iron. (*Coyle.*[271])

which the chromium was varied. These irons cover a range of from 2.80 to 3.90 per cent carbon and 2.00 to 2.50 per cent silicon. Reported tensile strengths usually show almost identical relative improvement with similar chromium additions.[158,240,356] An exception to this can be noted in Piwowarsky's work[169] where the addition of chromium increased the transverse strength of irons containing 1.00 to 2.75 per cent silicon only about 10 per cent, while with the same additions the tensile strength showed increases varying from 38 to 71 per cent. Deflections of low-chromium gray cast irons in the transverse tests showed a marked increase with additions of 0.25 to 0.40 per cent chromium and then fell to approximately the original values or lower when 0.50 per cent or more chromium was reached. When sufficient

chromium was introduced to render the cast iron cementitic, a sharp decrease in both strength and deflection resulted.

Although it is generally agreed that these results are representative of the increase of transverse strength, the accompanying increase in deflection reported in these experiments has been questioned as a generalization. Other experimenters, in unpublished work, found increase in transverse strength with decrease in deflection in certain chromium-containing cast irons. It is argued

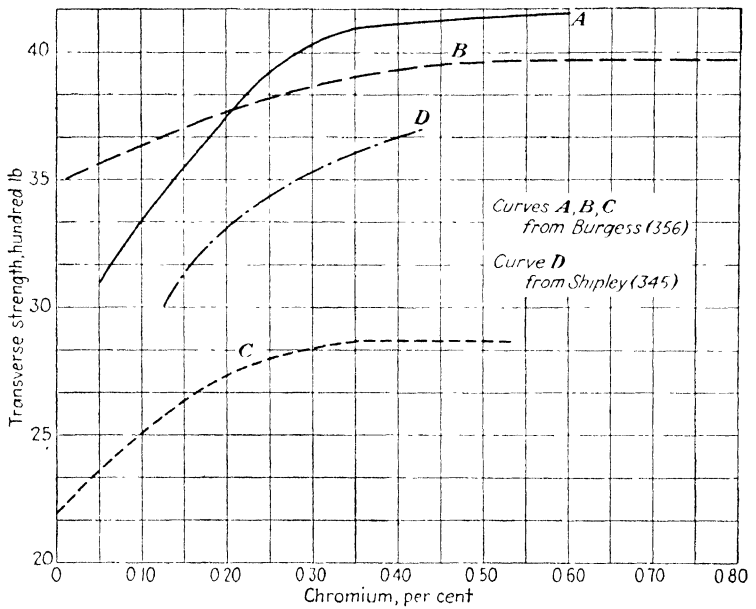


FIG. 168.—Effect of low chromium additions on the transverse strength of cast iron.

that this may be expected, owing to the fact that the pearlitic matrix has less ductility than the ferritic matrix. The counter argument points out that, while ferrite is more ductile than pearlite, the deflection is largely a function of graphite distribution, and that failure is instigated not by overstraining the matrix, considered as a whole, but rather by local overstraining in the paths between graphite plates. Thus, the size and distribution of the graphite plates become a determining factor, and the finer graphite plates, accompanying the pearlitic structure, result in higher deflection. This view is borne out by the experience of

most investigators that in gray-cast-iron test bars higher transverse strength is almost always accompanied by higher deflection.

The improvement in strength of cast iron by chromium is directly traceable to the production of a fine pearlitic groundmass in soft as well as hard irons, together with a more uniform or finer distribution of the graphite in both kinds of iron.

No dependable data are available on the effect of low chromium additions on the strength of white iron. The generally recognized increased wear resistance of chilled rolls and other chilled iron castings containing chromium probably results to some extent from the finer-grained core as a backing for the chilled surface and a more gradual gradient of hardness between the core and the chilled surface. It has also been demonstrated that the use of sufficient chromium insures the formation of a chill of controllable depth in which the pearlitic constituent may be rendered sorbitic or, with sufficiently rapid cooling, martensitic.

179. Impact Resistance and Fatigue Strength.—Chromium additions up to about 0.3 or 0.4 per cent have been found to increase the impact resistance[169] of gray cast iron. This effect might be anticipated from the fact that chromium inhibits the formation of large graphite plates and refines the groundmass. It is possible that a chromium ferrite is formed which imparts to the iron a characteristic "tough-hardness." No information is available on the effect of chromium on the impact resistance of irons that are cementitic.

Values of fatigue strength as a percentage of the tensile strength of cast iron show considerable variation as reported by different investigators. Values have been reported from 30 to 50 per cent of the tensile strength. In general, however, the value of fatigue strength of a cast iron of a given type was found to depend directly on the tensile strength. Any treatment tending to increase this latter value, whether heat treatment or alloy addition, increases the fatigue strength. Of particular interest in regard to low-chromium cast irons is the observation[355] that the fatigue strength of cast iron is lowered as graphite size increases. The effect of low chromium additions of limiting graphite size thus tends to increase fatigue resistance.

180. Thermal Conductivity.—Small chromium additions have been found to increase the thermal conductivity of gray cast iron.

Donaldson,[240] using a plain cast iron and two low-chromium cast irons, reported the values given in Table 152.

TABLE 152.—EFFECT OF CHROMIUM ON THE THERMAL CONDUCTIVITY OF CAST IRON*

Composition, per cent								Thermal conductivity, cal. per sec. per sq cm (°C. per cm.) at	
Total C	Combined C	Graphite C	Si	Mn	S	P	Cr	100°C.	400°C.
3.16	0 68	2 48	1 48	0 97	0 054	0 70		0 122	0 107
3 19	0 70	2 49	1 42	0 96	0 049	0 70	0 20	0 127	0 111
3.17	0 93	2 24	1.40	0 97	0 040	0 69	0 39	0.132	0 114

* Donaldson [240]

181. Effect of Low Chromium Additions on Wear Resistance.—The wear of cast iron is of considerable significance because many castings, such as cylinders and piston rings, are normally exposed to severe wear.

The opinion, based on service performance of chromium cast irons, that the presence of chromium considerably increases the wear resistance of cast iron, has long been widespread, and small percentages of this metal have been frequently added to cast iron that must resist abrasion. Specific data, however, were lacking on the quantitative effect of chromium until recently when a number of investigations on wear resistance of cast iron were undertaken by several experimenters.

A comprehensive investigation has been made by Klingenstein.[289] Heimes and Piwowarsky,[362] using machines designed to test both rolling and sliding friction, found that pearlitic irons always exhibited the greatest resistance to wear. This confirms the findings of Klingenstein.[289] Piwowarsky stated that an addition of chromium to a gray iron greatly increases the wear resistance, such an iron being three or four times as resistant as plain cast iron. Similar findings are noted by Klingenstein. Figures 169 and 170 illustrate the improvement Klingenstein found in wear resistance due to the presence of chromium and other alloy additions in irons as cast and after heating 3 hr. at 900°C. (1650°F.). It is apparent that the increased wear resist-

ance resulting from chromium additions in material as cast is also maintained when the chromium cast irons have undergone

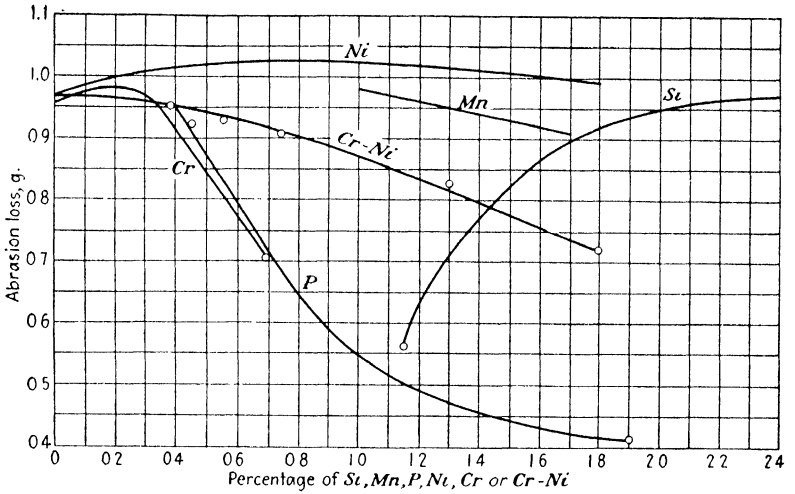


FIG. 169.—Effect of alloy additions on the abrasion loss of cast iron. (*Klingenstein.*[289])

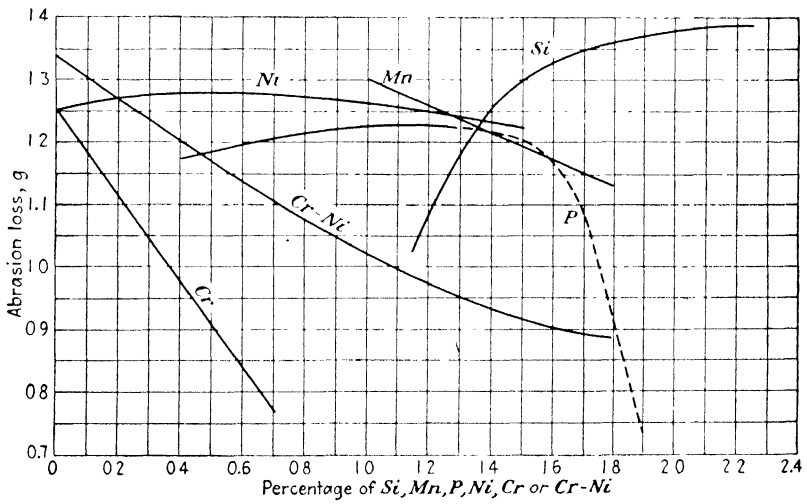


FIG. 170.—Effect of alloy additions on the abrasion loss of cast iron after heating 3 hr. at 900°C. (1650°F.). (*Klingenstein.*[289])

exposure to high temperatures. Klingenstein used a rotating cylinder of cast iron operating against a stationary cast-iron plate, the abrasion loss being the sum of the loss in weight of the fixed

and rotating parts. In his conclusions he stated that the use of chromium is particularly indicated for castings that are to be subjected to sliding wear at elevated temperatures, and a chromium content of as little as 0.2 per cent has a marked effect. This has been generally confirmed by Knittel.[392]

It has been found that unalloyed cast irons possessing the very fine type of graphite produced by casting normally white mixtures in heated molds do not possess such high wear resistance as pearlitic iron resulting from chromium additions. This has been attributed to the fact that eutectic graphite-ferrite areas are present in the former irons and act as starting points for wear. However, the wear resistance imparted by chromium carbide in pearlite may be sufficient to account for the difference.

D. EFFECT OF LOW CHROMIUM ADDITIONS ON HEAT RESISTANCE AND HIGH-TEMPERATURE STRENGTH

One of the limitations in the application of cast iron is caused by the changes which it undergoes on exposure to heat. These changes involve the growth of castings, decomposition and softening of the cast-iron groundmass, precipitation of additional graphite, and possible oxidation of the silicon. These alterations, in their first stages, result in diminished strength and wear resistance. As growth proceeds, the cast iron becomes extremely brittle.

The marked influence of small amounts of chromium in inhibiting or preventing these changes in cast iron on exposure to relatively high temperatures is generally recognized. A number of investigations have shown that this effect is marked with 0.25 per cent chromium[240] and increases as the chromium increases up to 1.0 per cent, the base iron and the temperature in question determining the minimum amount of chromium necessary.

The carbide formed with chromium is relatively resistant to decomposition at high temperature, with the result that the pearlitic structure tends to be retained. When sufficient chromium is present to give a cementitic structure, the free cementite likewise resists decomposition. For example, a white iron containing 3 per cent chromium cannot be softened or malleableized by any of the usual annealing treatments.

182. Growth at Elevated Temperatures.—Cast irons have been reported to show slight growth under the influence of tempera-

tures as low as 300°C. (570°F.). This growth increases and assumes serious proportions as the temperature increases. At temperatures above 800°C. (1470°F.) there have been instances where cast iron has increased 40 per cent in length. The growth appears to be due to several causes, principal among which are the decomposition of combined carbon, present either in pearlite or in massive form, into graphite and ferrite, followed by air penetration along the graphite plates producing oxidation of the iron or silicon-ferrite groundmass. Growth often is the direct cause of final rejection of cast-iron structural members and cast-

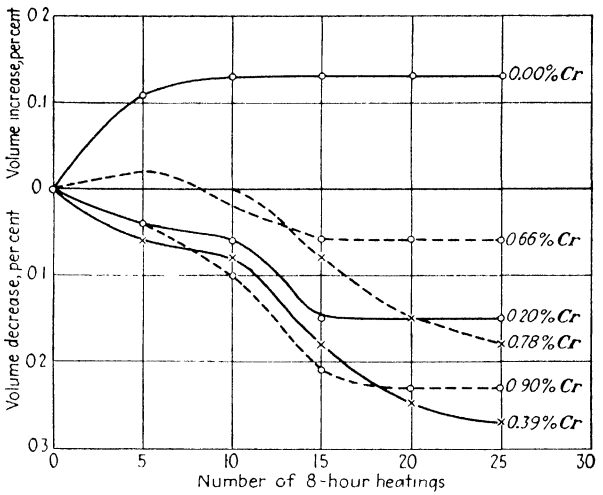


FIG. 171.—Effect of chromium on the volume change of cast iron on heating at 550°C. (1020°F.). (*Donaldson* [240])

ings such as grate bars and annealing boxes. Donaldson[240] and Burgess,[356] among others, have traced the effect of small chromium additions in inhibiting growth. Figures 171 and 172 illustrate the effect of small chromium contents in preventing growth on prolonged heating at two temperatures, 550 and 600°C. (1020 and 1110°F.). A similar effect at higher temperatures up to 870°C. (1600°F.) has also been noted. Chromium additions of approximately 0.35 to 1.0 per cent are generally used to prevent or reduce growth in gray cast irons, the chromium content being higher for higher exposure temperatures. Experiments have shown that this effect of chromium on growth is more than the counteraction of any opposite effect of silicon. For example,

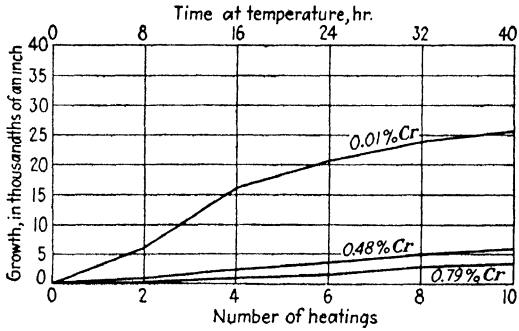


FIG. 172.—Effect of chromium on the growth of cast iron alternately heated to and cooled from 600°C. (1110°F.). (*Burgess.*[356])

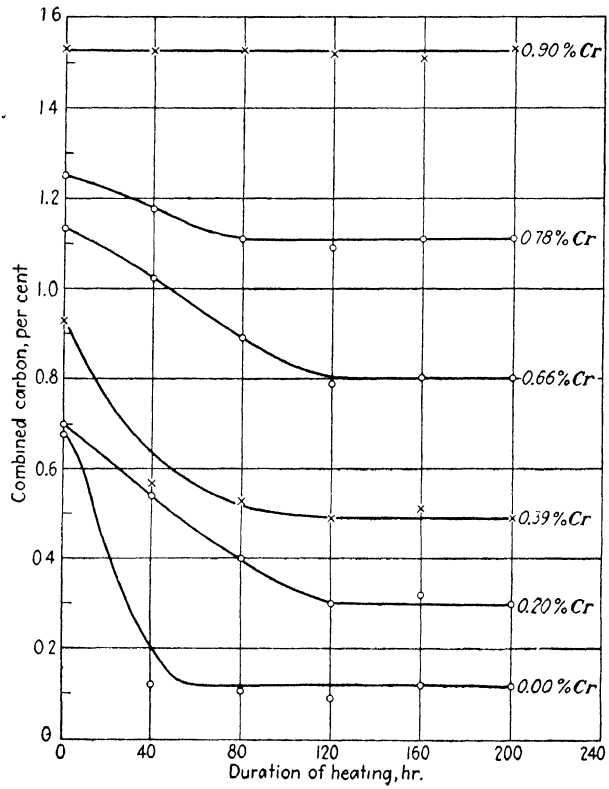


FIG. 173.—Effect of chromium on the stability of combined carbon on heating to 550°C. (1020°F.). (*Donaldson.*[240])

the silicon content of a chromium-free cast iron may be lowered 0.50 per cent and it will still show over two and one-half times as much growth on repeated exposure to an annealing cycle as a cast iron containing 0.50 per cent more silicon and 0.50 per cent chromium. This is at least partly due to the greater structural stability of the latter iron.

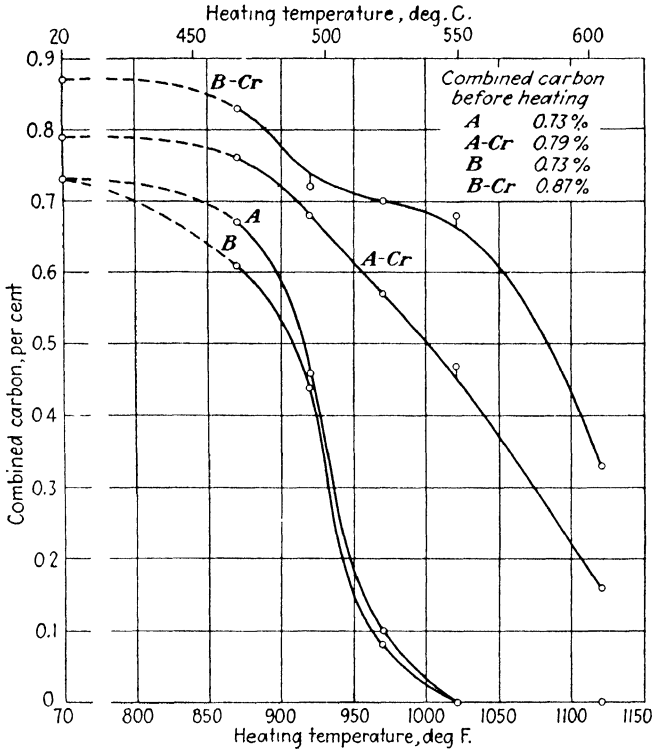


FIG. 174.—Effect of heating for 500 hr. on the combined carbon in cast iron containing chromium and nickel. See page 449 for composition. (*MacPherran and Krueger* [292])

183. Structural Stability and Retention of Hardness at Elevated Temperatures.—The structural stability on exposure to elevated temperatures conferred on cast iron by chromium additions is reflected by the higher final combined carbon, the higher Brinell hardness of the chromium irons after exposure, and their greater residual strength.[240,292,345,356,396] Figures 173 and 174 illustrate graphically the increased stability of the combined

carbon and, by inference, the stability of the pearlitic phase in chromium cast irons particularly below A_1. Figure 175 gives the degree of hardness retention in the same chromium-bearing irons as shown in Fig. 174. The composition of the irons used by MacPherran and Krueger[292] for securing the data shown in Figs. 174 to 177 is shown in the table at the top of page 449.

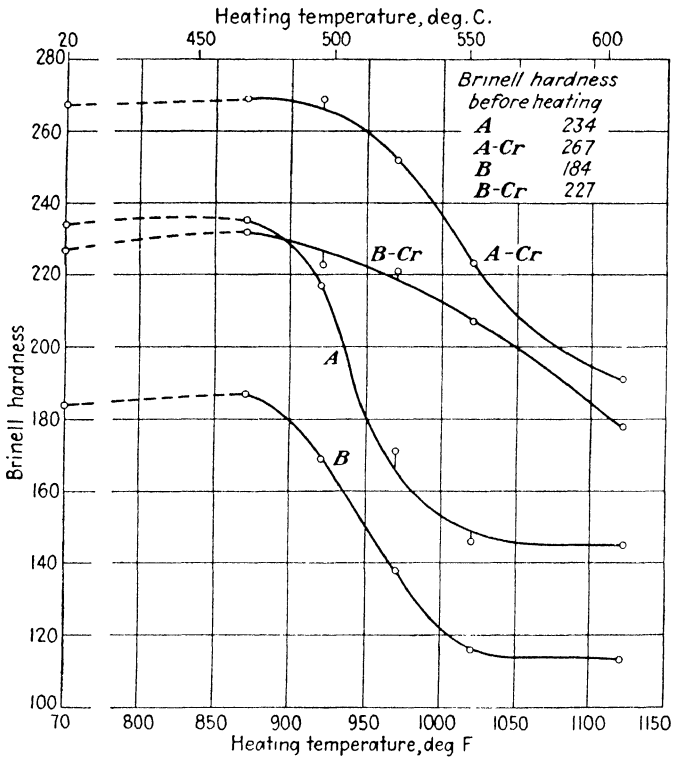


FIG. 175.—Effect of heating 500 hr. on the Brinell hardness of cast iron containing chromium and nickel. See page 449 for composition. (*MacPherran and Krueger.*[292])

184. Strength after Exposure to and at Elevated Temperatures. As might be anticipated from their structural stability, low-chromium cast irons exhibit greater strength at room temperature after exposure to elevated temperatures than do plain cast irons. This is illustrated in Fig. 176. The strength at elevated temperatures is also increased as may be seen in Fig. 177. An even more marked increase (Fig. 178) in high-temperature strength by

Symbol	Composition, per cent				
	Total carbon	Combined carbon	Si	Cr	Ni
A	2 96	0 73	2 53	0 02	0.96
A-Cr	2 67	0 79	2 39	0 45	0 76
B	3 63	0 73	1 15	0 03	0 03
B-Cr	3 46	0 87	1.36	0 54	0.01

the use of chromium was found by Donaldson.[273] He stated that with a chromium content of 0.39 per cent he found a breaking

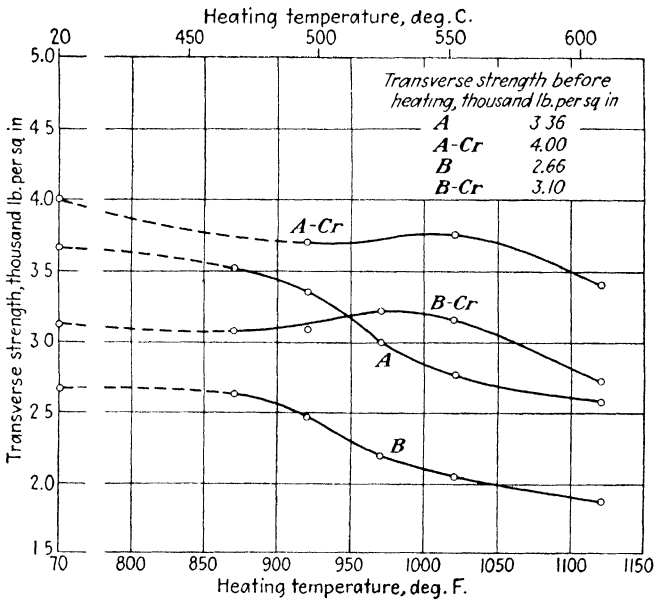


FIG. 176.—Effect of heating 500 hr on the transverse strength of cast iron containing chromium and nickel. Compositions are given above. (*MacPherran and Krueger.*[292])

stress of 34,900 lb. per sq. in. as compared with 24,600 lb. per sq. in. for a similar chromium-free iron when tested at 400°C. (750°F.) after exposure for 200 hr. at 550°C. (1020°F.). This effect was evident up to the maximum testing temperature of 600°C. (1110°F.).

E. MISCELLANEOUS DATA ON LOW-CHROMIUM CAST IRON

185. Effect of Low Chromium Additions on Corrosion.—Some improvement in corrosion resistance of gray cast iron in tap water,

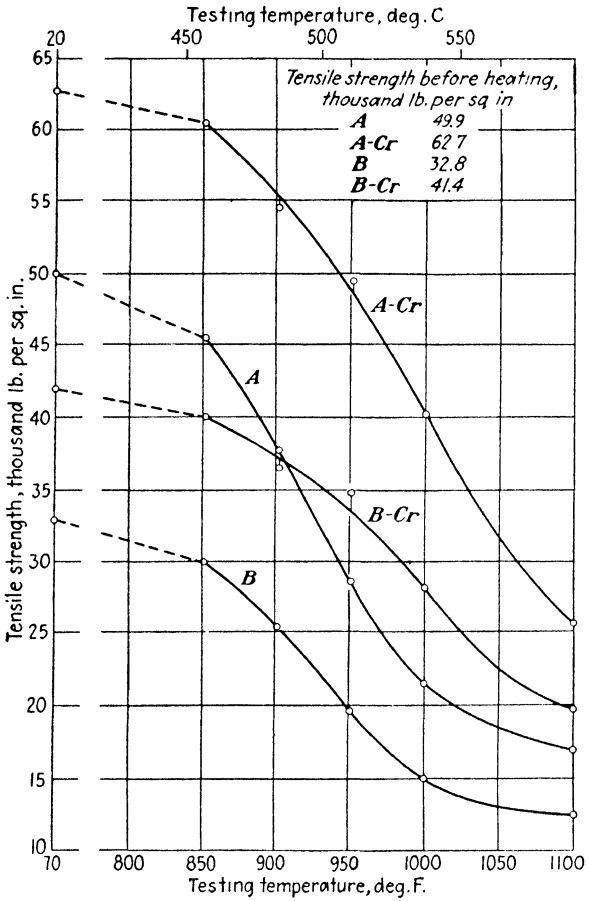


FIG. 177.—Effect of heating 500 hr. on the tensile strength of cast iron containing chromium and nickel. See page 449 for composition. (*MacPherran and Krueger.*[292])

sea water, and acids results from the addition of small amounts of chromium. Probably the most extensive experimental work has been done by Donaldson[240] and by Kötzschke and Piwowarsky.[222] In regard to the acids used in these tests, *viz.*, hydrochloric, nitric, and acetic, the improvement in the iron due

to the presence of chromium is slight. The improvement is much more marked in the case of sea water. Figure 179 taken from Donaldson's work illustrates this effect up to approximately 1 per cent chromium. The corrosion resistance continues to improve as chromium exceeds 1 per cent.

186. Uses of Low-chromium Cast Irons.—Low-chromium cast irons are employed in services demanding a higher strength than

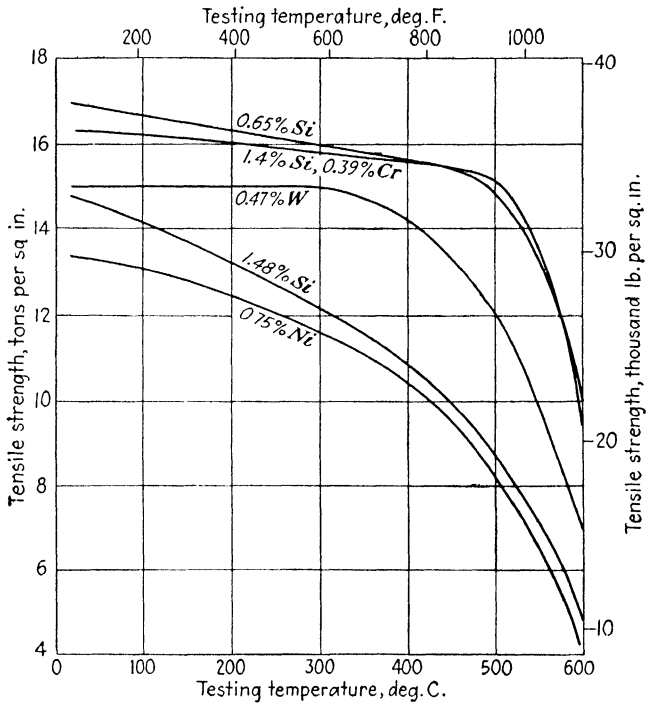


FIG. 178.—Effect of chromium on the tensile strength of cast iron at elevated temperatures. (*Donaldson.*[273])

is exhibited by plain cast iron. They are used particularly in installations where the castings are subject to heat or where wear resistance is important. Chromium is also used to modify a portion of a cupola charge where a few castings with special characteristics are needed.

A typical example in which the heat-resisting properties of low-chromium cast iron are utilized is in the form of grate bars. Bars containing approximately 0.40 to 1.0 per cent chromium have been adopted for use in municipal incinerators. Incorpo-

ration of approximately 0.50 to 1.25 per cent chromium in ingot molds and stools[281] has been found to increase their useful life considerably. The use of gray irons containing up to 0.75 per cent chromium is now common for wear-resistant castings as is the use of low chromium additions to rolls or other castings where a chilled, wear-resistant surface is required.

One of the widest applications of low-chromium cast irons is in the automotive field. It is estimated that 80 per cent of the automobile manufacturers are at present using cast irons containing from 0.11 to 0.50 per cent chromium in motor blocks, brake drums,

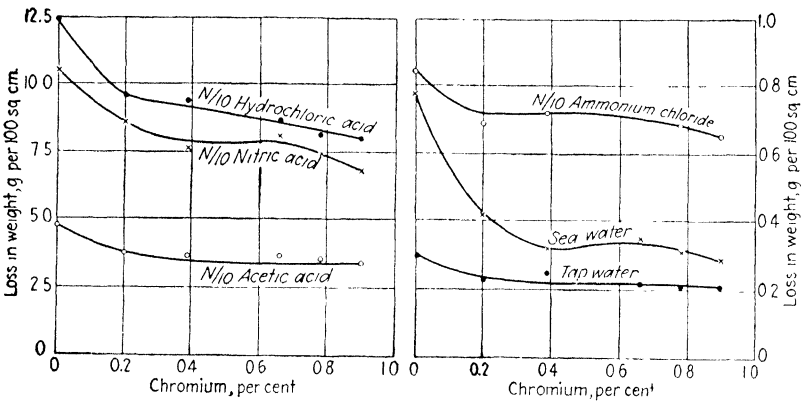


FIG. 179.—Effect of chromium on the weight loss of cast iron in acids, ammonium chloride, and water. The base iron contained 3.16 to 3.24 per cent total carbon, 0.68 to 1.53 per cent combined carbon, 1.40 to 1.60 per cent silicon, 0.95 to 1.00 per cent manganese, 0.040 to 0.070 per cent sulphur, and 0.66 to 0.77 per cent phosphorus. (*Donaldson.*[240])

and the like. In such applications chromium is used either alone or in combination with other alloys such as nickel, copper, and molybdenum.

The use of chromium additions to cementitic iron has been the subject of study. Improvement of the wear resistance of such irons is indicated by the adoption of iron balls containing 2.0 to 2.5 per cent chromium and 0.80 per cent silicon in ore-concentrating plants.

When small percentages of chromium are added to malleable iron castings,[390] a final structure consisting of temper carbon and pearlite plus ferrite or a completely pearlitic matrix may be produced. The ductility of such irons is reduced and the strength and wear resistance are markedly increased. As usual with

chromium irons, an optimum balance of the chromium-silicon ratio exists.

187. Chromium-silicon Cast Irons.—These irons may in general be considered as simple low-chromium cast irons with normal or only slightly modified silicon content. Thus in a sense this entire chapter deals with chromium-silicon cast irons. The microstructure and correlative properties of these irons have been described in detail, and in the foregoing discussion it has been indicated that in any reasonably small section, cast-iron structures similar to those obtained with balanced chromium and silicon may be produced in non-alloyed low-silicon cast iron. It is necessary, however, in such unalloyed iron to control carefully the silicon and carbon contents and to keep them in proper range with respect to the section to be cast. Moreover, this range is highly critical, so that minor variations have marked effects on the resulting structure and properties. In addition, this balance is highly sensitive to changes in section, so that it is impracticable to obtain satisfactory results in castings having even moderate changes in section. Likewise, in the case of uniformly heavy sections the tendency for change of structure between surface and center results in a non-uniform structure of the castings. The use of higher silicon with chromium tends to overcome these objections to the unalloyed low-silicon irons.

For certain applications, the low-silicon, chromium-free irons have satisfactory properties. However, they frequently lack many of the properties obtained with the chromium-silicon irons, such as stability of the carbides, resistance to growth, increased strength with accompanying toughness, and wear resistance. Therefore, while unalloyed irons might be considered the equivalent of the chromium-silicon irons from the standpoint of metallography, they are not to be put in the same category from the standpoint of the foundryman and the engineer.

In the previous discussion, little attention has been paid to the method of silicon addition. Silicon may be added in the charge or in the ladle. When added in the charge, it may be present in the base pig iron or as a special iron alloy containing up to 75 per cent silicon. The silicon added in the ladle is generally in the form of ferrosilicon, and improved properties are noted when an appreciable proportion of silicon is added late in the heat as

ferroalloy in the ladle or as briquettes in the hearth. The briquettes added with the charge pass through the cupola and deliver the molten ferrosilicon to the hearth, so that the effect is similar to that of a ladle addition. Because late silicon additions improve the mechanical properties of chromium-containing cast irons, material made in this way might well be classified as chromium-silicon cast iron even though there is no distinction in the final chemical analysis.

188. Other Special Low-chromium Cast Irons.—The alloy cast irons containing low chromium and one or more other alloys are discussed in detail in previous monographs of this series[360,420,421] or in monographs now in preparation.† For that reason, no more than the briefest mention of these complex cast irons is justified here.

The combined effect of nickel and chromium in cast iron has been thoroughly investigated. Nickel dissolves in the ferrite, thus increasing the strength and toughness of the matrix. It also acts as a graphitizer when added in small amounts, possessing approximately one-half the graphitizing power of silicon. As a certain minimum amount of a graphitizing material must be present in a cast iron to insure machinability and this minimum increases gradually with the chromium content, it is possible to estimate rather accurately the amount of nickel plus silicon that should be present in a given low-chromium iron. Considerable difference in opinion exists, however, on the relative amounts of nickel and chromium that should be present.

Recommendations vary from no nickel to a nickel content three times the chromium content and higher. Irons are actually produced in as great a range of nickel-chromium combinations as are indicated by the above statement. In general, chromium does not exceed 0.75 per cent and nickel 2 per cent. The most important factor in gray irons is that the silicon-plus-nickel content be sufficiently high to insure machinability. The International Nickel Company has found that a nickel content of 1 to 2 per cent is normally to be recommended if nickel is the sole alloying addition, and that a nickel-chromium cast iron of relatively low silicon content should contain approximately 0.50 per cent chromium and 1.50 per cent nickel.

* This has been discussed in "The Alloys of Iron and Carbon," Vol. II,[478] pp. 310–323.

† "The Alloys of Iron and Nickel," "The Alloys of Iron and Vanadium."

Copper acts as a graphitizer of cast iron and has been used for this purpose in low-chromium cast irons. To date the amount of added copper has been held to approximately 1 per cent maximum in such combinations. One grade of cast iron, notable for moderately increased corrosion resistance to tap water, steam, and atmospheric conditions, contains approximately 0.50 per cent copper and 0.50 per cent chromium. Copper and copper-chromium cast irons have been discussed in detail by Gregg and Daniloff.[421]

There are a few other alloy cast irons containing chromium which are used to a limited extent or which have come into wider use lately. Included in these are chromium-titanium and chromium-molybdenum cast irons. The latter have been described in detail in a previous monograph.[360] Chromium-aluminum cast irons have also been produced and have been successfully nitrided.

F. AUTHORS' SUMMARY

1. Low-chromium cast iron is material of considerable engineering importance. While cast iron has frequently been taken for granted by the engineer as so much weight and so much bulk, improvements in uniformity of production and increased mechanical properties of the iron have, together with its recently discovered high damping capacity, made this point of view obsolete. One important factor in this change of view has been the production of pearlitic cast iron with its correlative mechanical properties. Chromium is frequently used in small amounts to obtain this structure.

2. Although there are several methods of adding chromium to cast iron, the use of chromium briquettes in which ferrochromium is bonded with cement and put through the cupola with the charge seems to give the most consistent results. The cement protects the chromium from oxidation in the shaft and disintegrates, releasing the chromium in the melting zone. Another method in common use involves the addition of crushed ferrochromium to the cupola stream or ladle. Either method gives high chromium recovery.

3. In addition to producing pearlitic cast iron, chromium produces finer graphite flakes, eliminates free ferrite, and stabilizes the carbides. The structure of the chromium cast iron is maintained over an appreciable range of silicon, but for optimum

results silicon and chromium should be balanced for the section to be cast. Chromium tends to eliminate differences in structure with differences in section. Although insufficient data are available for a quantitative summary showing the relationship

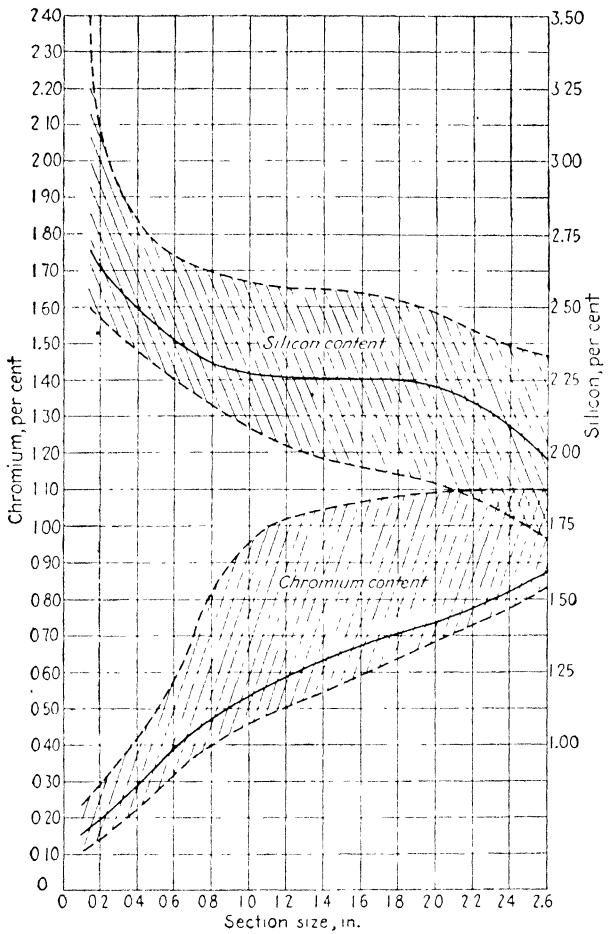


FIG. 180.—Approximate silicon and chromium contents for different sections. (*Union Carbide and Carbon Research Laboratories, Inc.*)

between silicon and chromium contents and section, much has been done along this line, and the desired relationship for usual sections may be obtained from the discussion in this chapter. An approximate relationship curve is given in Fig. 180. The areas shown vary with the carbon content, type of sand, and the

like, and are drawn for average conditions. Figure 180 represents the authors' judgment of the probable optimum balance and should be used with caution as it is obviously impossible to specify exactly the optimum silicon and chromium contents for a given section size of cast iron in a summary curve because of the varying purposes for which chromium may be added to cast iron. It is, however, possible to show an approximate trend for the silicon and chromium contents normally used in various sections of gray cast iron containing a normal carbon content, *i.e.*, 2.90 to 3.30 per cent. It will be noted from Fig. 180 that relatively wide ranges of both silicon and chromium contents are possible, particularly in the heavier sections. The ranges have been chosen to yield an iron with a minimum hardness of approximately 180 to 200 Brinell in the lowest chromium and highest silicon ends of the respective ranges, and an iron just within the machinable limit with the maximum chromium and minimum silicon contents shown on the curve.

4. It is difficult to fix the optimum chromium and silicon contents in a particular iron because chromium may be added (*a*) to decrease growth and increase heat resistance, in which event the maximum chromium and the lowest possible silicon would be employed; (*b*) to improve wear resistance, in which event a relatively high chromium would be used and a silicon content somewhat above the minimum, depending on the machining necessary; and (*c*) to improve mechanical properties, in which event an intermediate chromium content in the allowable range would be employed with an iron of a given silicon content, sufficient to obtain the desired strength increase without adversely affecting the machinability. The section sizes shown as the abscissas in Fig. 180 are considered as portions of a casting made in dry or green sand, cooling normally in the mold. The amounts of chromium and silicon in a given casting are usually governed by the amounts suitable for the smallest section, particularly if these thin sections must be machined and are not delayed in their cooling by proximity to heavier sections.

5. Curves are included in Fig. 180 within the allowable chromium and silicon ranges indicating approximate chromium and silicon contents desirable for high strength with ready machinability. However, the error possible in such curves is very great in view of the wide variation in base cast irons that may be

employed, and any such fixing of the optimum chromium-silicon ratio must be considered only an approximation. One of the largest factors in such variations is the difference in total carbon. Although insufficient information is available to evaluate definitely this effect, it would appear that taking a base iron containing 3.20 per cent carbon the silicon should be increased or decreased approximately 0.10 per cent for each corresponding decrease and increase of 0.10 per cent carbon. Thus, for a given purpose, if an average of 2.0 per cent silicon is found optimum in a 0.50 per cent chromium iron containing 3.2 per cent carbon, the silicon average can be advantageously increased to approximately 2.30 per cent if the carbon is lowered to 2.90 per cent in a similar type of iron.

6. The structural characteristics of chromium cast iron are reflected not only in the mechanical properties at room temperature but in better retention of these at high temperature, growth at subcritical temperatures being practically eliminated by the presence of chromium. The machinability of chromium cast iron of balanced analysis is not seriously affected by the chromium, although moderate differences may be found as would be expected of cast iron with higher strength. The fatigue strength probably bears the usual relationship to tensile strength. The wear resistance of chromium cast iron is particularly high and is probably due to the nature of the carbide. Excess amounts of chromium or, more accurately, an excess ratio of chromium to silicon in cast iron of a given section produces primary cementite. Chromium iron containing some massive cementite has as many disadvantages as mottled iron without chromium, but is highly wear resistant. Chromium iron containing massive cementite has increased corrosion resistance, but the mechanical properties are of the same order as is to be expected from any white iron.

7. Chromium is useful in cast iron to be heat treated in that the graphite flakes are smaller and the matrix responds more readily to rapid cooling. Further increase in strength and deflection of chromium cast iron is produced by late silicon additions to the molten iron, either by means of briquettes in the cupola or alloy addition to the stream or ladle. Nickel, copper, and other graphitizing agents are also used in chromium cast iron, and a large tonnage of chromium cast iron contains nickel as an additional strengthening and toughening agent.

8. The use of chromium cast iron for engineering purposes covers not only parts of agricultural machinery, crusher jaws, glass molds, grate bars, and the like, but also the more recent applications such as crankshafts, camshafts, gears, cylinder blocks, and other members intended for strictly engineering purposes.

CHAPTER XIII

CHROMIUM ENGINEERING STEELS CONTAINING 4 TO 10 PER CENT CHROMIUM

Plain Chromium Steels Containing 4 to 10 Per Cent Chromium—Modified Chromium Steels Containing 4 to 10 Per Cent Chromium—Authors' Summary

The chromium engineering steels containing 4 to 10 per cent chromium, either plain or modified by the addition of one or more other alloying elements, form an important class of industrial products. They are usually made in the electric furnace and present no great difficulty in either melting or hot working, and, when the composition is correctly balanced, they possess high strength and wear resistance together with sufficient corrosion and oxidation resistance for satisfactory application in oil refineries and for valves in internal-combustion engines. "Silchrome" valves containing 8.00 to 9.75 per cent chromium and about 3.50 per cent silicon are used widely in automobile engines.

A. PLAIN CHROMIUM STEELS CONTAINING 4 TO 10 PER CENT CHROMIUM

Despite the fact that the medium-chromium steels are not so corrosion resistant as the grades containing more than 10 per cent chromium, they are the most widely used material for oil-still tubes handling corrosive oils. The explanation for this is that they are probably the most satisfactory moderately priced steels which have been developed for the purpose. Moreover, they combine satisfactory strength and oxidation resistance at the temperatures used with the property of elongating when overstressed, thus indicating in advance their impending failure.

189. Manufacture.—The production of the 4 to 10 per cent chromium steels has been almost entirely from the electric furnace, although it is likely that the open hearth can be used if sufficient care is taken with slag and temperature regulation. The principal reason for using the electric furnace has been to

avoid the loss of chromium that would result from open-hearth practice as ordinarily conducted since the chromium additions are too large to be made in the ladle. The details of melting and pouring heats of high-chromium steels have been described in the literature and necessarily are dependent to some extent upon the local conditions, that is, type of scrap available, the cost of power, the specifications for the finished product, and others. These factors are so varied that little can be said except in very general terms. However, there are certain fundamental principles that can be stated, one of paramount importance being the avoidance of oxidation of the chromium during the melting of the charge. This is obviously important because it involves the loss of chromium and, more particularly, because of the unfavorable influence of oxide inclusions on the non-corrodibility and mechanical properties of the product. Under some conditions, oxides may give rise to inclusions that almost certainly will reduce the corrosion resistance of the product. These remarks are general and apply to the 4 to 6 per cent chromium range, although not to the same extent as to the steels with higher chromium content because the corrosion resistance of lower chromium steels is not of the same high degree as that obtainable in the higher chromium ranges and the resistance is, therefore, not so critical in character.

190. Critical Points.—The critical points in 4 to 10 per cent chromium steels with various contents of carbon and other elements are shown in Table 153. Naturally, the position of the critical points in the various chromium steels is influenced to a marked degree by other elements that may be present.

The reader will find detailed thermal-equilibrium data on these and other chromium steels in Chapter IV; the following items are particularly pertinent here:

1. The carbon content of the pearlite is reduced by chromium, so that at about 6 per cent chromium the pearlite contains not more than 0 5 per cent carbon, as shown by Monypenny.[338]

2. The effect of chromium in the iron-chromium solid solution is apparently to reduce the solubility of the carbides, which in turn affects their rate of diffusion and thus the facility with which the changes upon heat treatment take place; this gives a characteristic sluggishness to the chromium steels which is particularly noteworthy in the 4 to 10 per cent chromium steels containing high carbon—a very important factor in their commercial heat treatment.

3. The composition of the chromium carbides is a function of at least three factors, namely:

a The amount of chromium present.

b. The amount of carbon in the steel.

c. The rate of cooling.

The presence of certain other alloying elements also enters into this already complicated situation. To name only a few of such elements, copper, molybdenum, tungsten, titanium, and columbium are frequently found in the 4 to 10 per cent chromium steels.

TABLE 153.—CRITICAL POINTS IN STEELS AND LOW-CARBON ALLOYS CONTAINING 1 TO 10 PER CENT CHROMIUM

Composition, per cent				Temperature, °C.			Reference No.
C	Cr	Si	Mn	Hardening*	A_3	A_2	
0 100	0 99	0 17	0 39	869			407
0 108	3 15	0.30	0 42	857			407
0 099	5 21	0.34	0 50	835			407
0.103	7 20	0.32	0 46	832			407
0.200	0 97	0.19	0 38	841			407
0 191	3 04	0 28	0 45	837			407
0 207	5 19	0.35	0 51	832			407
0 201	7 18	0.30	0 52	835			407
0 310	1 06	0 26	0 42	823			407
0 299	3 14	0 27	0 52	823			407
0 301	5 27	0.28	0 39	834			407
0 299	7 26	0.33	0 54	832			407
0 38	4 58	0 21	0 04		816		378
1.44	4 77	0 09			801		378
	3 8†	0 0			874		204
	6 6†				843		204
	8 4†				845		204
	9 9†				874		204
0 03	1 12		0.30		878		204
0 03	2 20		0 30		831	755	378
0.03	3.50		0.38		815	769	378

* End of critical range on heating, values were obtained by the differential method using nickel as a neutral body.

† A very pure series of steels with carbon and manganese contents between 0.01 and 0 04 per cent respectively.

4. The change from alpha to gamma iron is not greatly influenced by increasing chromium content, but the change from gamma to delta is greatly affected by chromium contents up to 7 or 8 per cent, and with higher chromium it is profoundly affected so that, at about 14 per cent chromium and low carbon, the gamma-delta change on heating disappears.

Specifically, the rate of variation of position of the carbide change point is shown in Fig. 37, page 65. It should be noted that the Ar_1 point is raised nearly 100°C. (180°F.) between 0 and 10 per cent chromium. Wright and Mumma[407] confirmed practical conclusions regarding the position of the critical points as evidenced by the tensile strength and hardness, *i.e.*, hardening temperatures should be over 875°C. (1605°F.), while maximum toughness is attained by tempering at 650°C. (1200°F.) or higher. In this connection, it has been shown that as the chromium is increased while carbon is maintained constant the effective critical temperature is raised until the ratio of chromium to carbon is about 10 to 1; further increase of chromium above that ratio causes a progressive depression in the critical temperature. Likewise with constant chromium, increase of carbon to the ratio of 1 part of carbon to 10 parts of chromium results in a raising of the temperature. Exceeding the 1 to 10 ratio causes a depression of the critical temperature.

Russell[101] reported differential and inverse-rate cooling curves on steels which unfortunately did not have carbon contents below 0.25 per cent, although the chromium varied from about 1.5 per cent to slightly more than 12 per cent. With between 0.4 and 0.5 per cent carbon and chromium from 1.49 to 13.22 per cent, the Ac_1 point was raised from 771 to 819°C. (1420 to 1506°F.). In a similar series of steels in which the spread of chromium content was roughly the same (1.54 to 15.02 per cent), but with carbon contents between 0.8 and 0.9 per cent, the critical ranges were nearly the same.

However, these minutiae are chiefly of scientific interest, and enough is known of the practical features of the heat treatments to warrant rather positive statements respecting heat-treating temperatures—namely, that the 4 to 7 per cent chromium steels without significant amounts of other elements are hardened by normal or rapid cooling after holding at temperatures above 900°C. (1650°F.) and that they are sufficiently annealed by slow cooling from temperatures between 750 and 770°C. (1380 and 1420°F.).

191. Mechanical Properties.—The most comprehensive information yet published on the tensile properties of the chromium steels discussed in this chapter is that of Wright and Mumma.[407] Their work was done on steels with roughly 1, 3, 5, and 7 per cent

chromium, in series containing 0.1, 0.2, and 0.3 per cent carbon respectively. The hardening temperatures were those found to be appropriate as a result of some preliminary hardening tests; this was 900°C. (1650°F.) for steels containing 1 and 3 per cent chromium with 0.10 per cent carbon and 875°C. (1605°F.) for

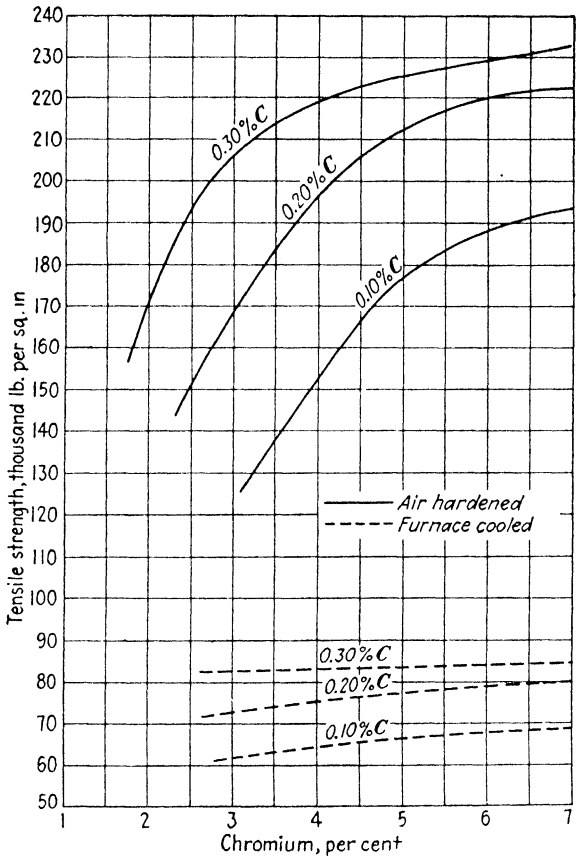


FIG. 181.—Effect of carbon and of chromium on tensile strength. (*Wright and Mumma.*[107])

all others. The tempering was done at 550, 600, 650, 700, and 750°C. (1020, 1110, 1200, 1290, and 1380°F.) respectively. The data are summarized in Figs. 181 and 182. In Fig. 181 the tensile-strength values corresponding to single tempering temperatures are given. The treatment used was that which gave the combination of highest tensile strength with about the average

ductility. This simplification presents a concise picture of the variations due to chemical composition. The curve in Fig. 182 shows the inverse relationship between the tensile strength and the ductility for the steels as a whole, the individual points being plotted to show the scatter.

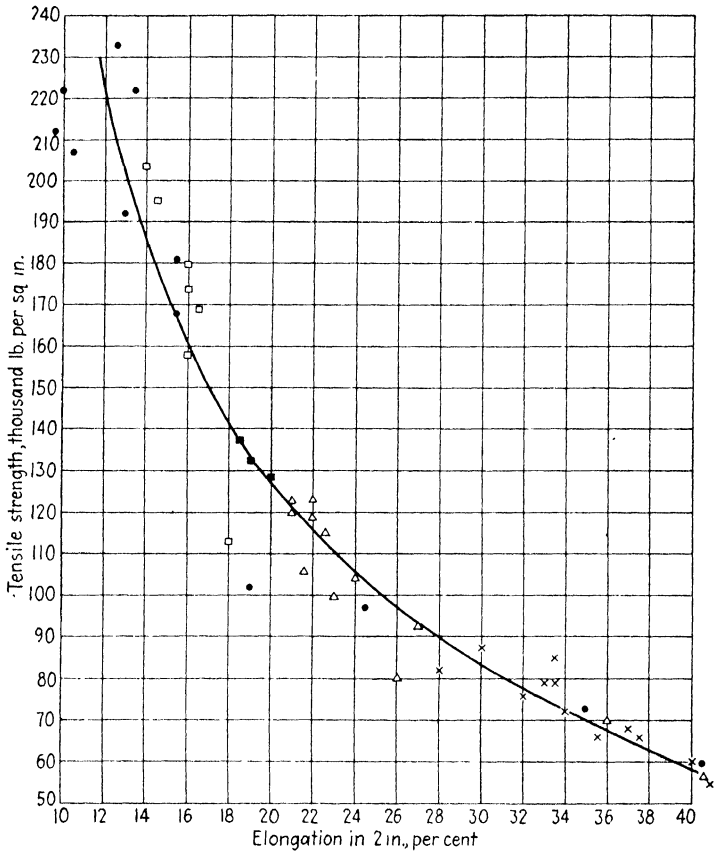


FIG. 182.—Relation of tensile strength to elongation in medium-chromium steels. (*Wright and Mumma.*[407])

B. MODIFIED CHROMIUM STEELS CONTAINING 4 TO 10 PER CENT CHROMIUM

So far the principal effort at modification of the 4 to 10 per cent chromium steels has been (1) to add molybdenum, tungsten, copper, silicon, or nickel and (2), recently, to add columbium or titanium. Molybdenum and tungsten are used to increase the

tensile properties and the resistance of the steels to deterioration as a result of prolonged heating. It may be added that two schools of thought have developed concerning the merits of the additions, one in favor of molybdenum and the other of tungsten. Columbium and titanium have been added to decrease air-hardening tendencies. As far as the specific effects of small amounts of the more common alloying elements are concerned, it would be expected that copper, silicon, and nickel, when added in fractions up to 1 per cent, either singly or together, would increase the surface stability of these steels. Silicon above about 1.5 per cent is likely to affect unfavorably the workability of the steels for seamless-tube manufacture and is usually present to the extent of 0.6 or 0.7 per cent at most. Nickel up to 0.75 per cent does not harm the working properties.

192. Properties of Steels Containing 4 to 10 Per Cent Chromium Modified with Molybdenum and Tungsten.—Molybdenum is used extensively as an addition element to 4 to 6 per cent chromium steels. Not only are the room-temperature properties increased slightly (Table 154), but the properties at elevated temperatures are markedly affected. Typical creep values for 1 per cent elongation in 10,000 hr. at 480°C. (900°F.) indicate an increased creep limit of some 8000 lb. per sq. in. due to the addition of 0.5 per cent molybdenum. At 540°C. (1000°F.), the increase is approximately 3500 lb. per sq. in., and at 595°C. (1100°F.) the increase in creep limit is approximately 2000 lb. per sq. in. according to Wright.[462]

The 4 to 6 per cent chromium steels with 0.5 per cent molybdenum are also used in the cast state, with subsequent annealing, normalizing, and tempering. A.S.T.M. specification A-157-36[464] requires annealing from above the critical temperature by slow cooling to at least 260°C. (500°F.), normalizing by cooling from above the critical range in still air, and tempering by heating to at least 85°C. (150°F.) above the temperature to be encountered in service for not less than 1.5 hr. for inch or less of wall thickness. This is followed by cooling in the furnace or in still air. A minimum tempering temperature of 425°C. (800°F.) is stipulated. This treatment results in room-temperature properties of 100,000 lb. per sq. in. tensile strength, 65,000 lb. per sq. in. yield strength, and minima of 18 per cent elongation in 2 in. and 30 per cent reduction of area. A steel containing 0.20 to 0.25 per cent

TABLE 154.—ROOM-TEMPERATURE AND ELEVATED-TEMPERATURE PROPERTIES OF PLAIN AND MODIFIED 4 TO 6 PER CENT CHROMIUM STEELS

Specimen No.*	Composition, per cent						Room-temperature tensile properties					Short-time tensile properties at elevated temperatures						Creep stress, lb./sq. in.†
	C	Mn	Si	Cr	Mo	W	Tensile strength, lb. sq in	Yield strength, lb /sq in.	Elongation in 2 in , per cent	Reduction of area, per cent	Brinell hardness	Temperature of test °C	Temperature of test °F	Tensile strength, lb /sq in	Yield strength, lb. /sq in	Elongation in 2 in., per cent	Reduction of area, per cent	
1	0 10	0 45	0 18	5 09	0 55		66 600	19,000	39 0	80 5	128	425	800					14,250
												540	1000	44,500	7,500	28 5	73 5	7,200
												650	1200	25 800	1,500	46 0	91 0	900
2	0.14			4 to 6			61,050	29,200	38 8									
3	0 14			4 to 6	0 5	.	62,100	31,250	37 6									
4	0 14			4 to 6	....	1	70,200	34,130	35 2									
5	0 12			5	....	..						425	800				.	21,000
6	0 20			5	0.5	.						480	900	..	.			24,000
7	0 22			5		1						425	800					27,000

* Data for specimen 1 from Clark and White.(468) Data for specimens 2 to 7 from Wright (462)

† The creep rate for specimen 1 was 0.01 per cent in 1000 hr; for specimens 5, 6, and 7 it was 1 per cent in 10,000 hr.

carbon with 4.5 per cent chromium and 0.5 per cent molybdenum gave the following properties after normalizing and tempering at the specified temperatures:

Property	Tempering temperature		
	690°C. (1275°F.)	775°C. (1425°F.)	830°C. (1525°F.)
Tensile strength, lb. per sq. in..	114,000	89,500	83,700
Yield strength, lb. per sq. in....	89,400	60,300	43,400
Elongation in 2 in., per cent....	20	28	31
Reduction of area, per cent	52	61	64
Brinell hardness	233	179	165

Short-time tensile properties together with the creep limit of 5 per cent chromium, 0.5 per cent molybdenum cast steels containing approximately 0.32 per cent carbon are shown in Fig. 183, as determined by Maack.*

The 4 to 6 per cent chromium steels with 1 per cent tungsten are also used industrially, both in the forged or rolled condition and as castings. Wright[462] gave the room-temperature properties in the annealed state as yield strength 34,000 lb. per sq. in., tensile strength 70,000 lb. per sq. in., and elongation 35 per cent, and indicated a creep limit intermediate between that of the steel containing 5 per cent chromium and 0.5 per cent molybdenum and that of the plain 5 per cent chromium steels. In two papers Malcolm[369] and associates[405] reported tensile and creep properties, heat treatments, and recommended specifications for cast chromium-tungsten steels. Some of the results, augmented by unpublished data supplied by Malcolm, are given in Figs. 184 and 185. The recommended heat treatment involves normalizing from 955°C. (1750°F.), renormalizing from 900°C. (1650°F.), and tempering at 675°C. (1250°F.). Malcolm and Jones[454] further stated that the matter of heat treatment of castings is of very great importance.

The occasional embrittlement of the 4 to 6 per cent chromium steels with or without molybdenum or tungsten additions has been a matter of great concern and much discussion. Many years of

* Private communication.

service indicate that both the molybdenum and the tungsten modification of these steels are free from temper brittleness in the usual sense, and there is no definite proof that the 4 to 6 per cent chromium steel without modification lacks ductility at service temperatures, although service tests have shown that the addition of either molybdenum or tungsten is desirable from many

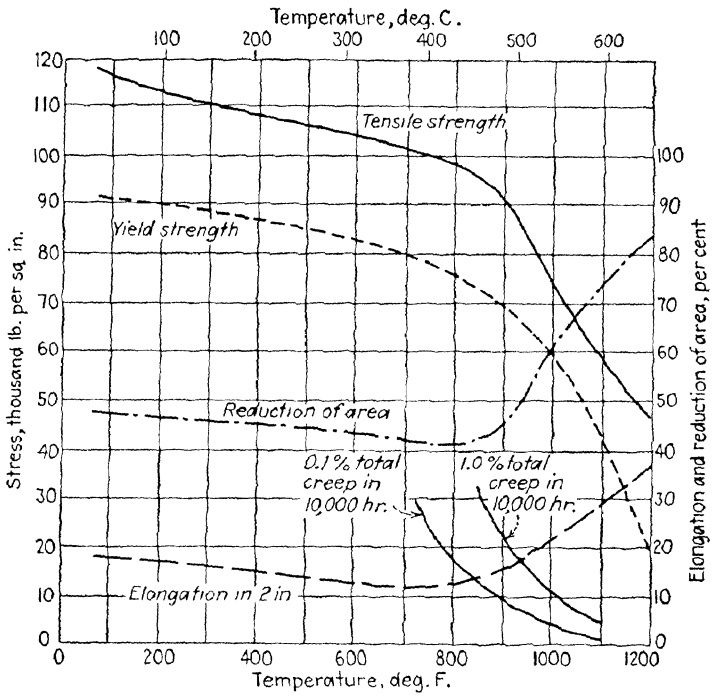


FIG. 183.—Elevated-temperature properties of a steel containing 0.32 per cent carbon, 5.0 per cent chromium, and 0.5 per cent molybdenum. (*Courtesy of H. W. Maack.*)

points of view, grain refinement and generally improved ductility being the major factors.

The room-temperature and short-time elevated-temperature properties of three steels containing 8 and 9 per cent chromium modified with 21 per cent nickel, 7.7 per cent tungsten, and 3.5 per cent silicon, respectively, reported by Clark and White,[210] are given in Table 155.

193. Properties of 4 to 10 Per Cent Chromium Steels Modified by Columbium and Titanium.—One of the tendencies to be

carefully controlled in these steels is the occurrence of air hardening. Annealing is resorted to with practically all rolled products. This hardening tendency also makes itself felt after welding operations, and some form of heat treatment is generally employed, such as reheating of the welded portion or an anneal of the whole article where feasible. The annealing is accomplished by holding

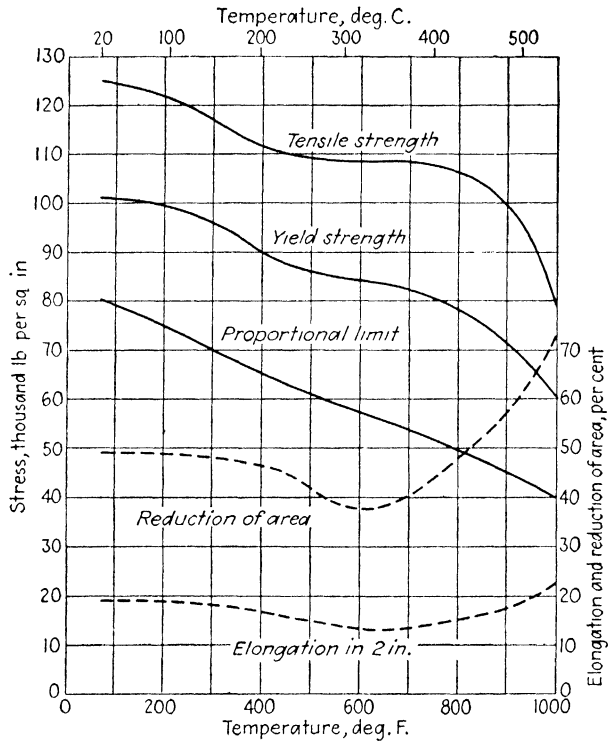


FIG. 184.—Elevated-temperature properties of a cast steel containing 0.25 per cent carbon, 0.53 per cent manganese, 0.42 per cent silicon, 5.87 per cent chromium, and 0.80 per cent tungsten. (*Malcolm.*)

the metal for a short time at 700 to 800°C. (1290 to 1470°F.) but not exceeding the latter temperature; it is often sufficient to hold the metal only a few moments at temperature, particularly in the case of small welds.

The addition of small amounts of strongly carbide-forming elements such as columbium and titanium has a marked effect on reducing the air-hardening tendency. The general rule has been fixed that columbium should equal 7 to 10 times the carbon

content and that titanium should equal 6 to 8 times the carbon. When so alloyed, the steel is much softer and may suffer considerable cold work without difficulty.[414] The marked effect of the columbium additions on the softening of the steels in the as-rolled condition is shown by data obtained by Becket and Franks[414] which are reproduced in Table 156.

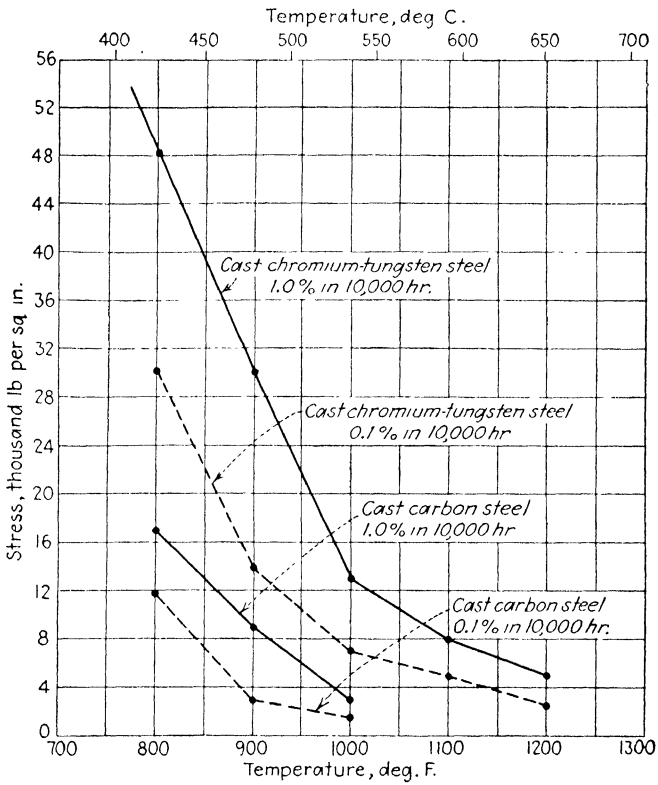


FIG. 185.—Creep stresses at 425 to 650°C. (800 to 1200°F.) of the cast chromium-tungsten steel whose short-time elevated-temperature properties and composition are given in Fig. 184 The cast carbon steel contained 0.35 per cent carbon. (*Malcolm.*)

194. Oxidation Resistance of the Plain and Modified Steels Containing 4 to 10 Per Cent Chromium.—The steels with 4 to 10 per cent chromium are not usually thought of as being resistant to oxidation in the same sense as the high-chromium steels and irons. It has been found, however, that the addition of less than 1 per cent titanium to a 7 to 9 per cent chromium steel so

TABLE 155.—ROOM-TEMPERATURE AND ELEVATED-TEMPERATURE PROPERTIES OF ANNEALED MODIFIED 8 AND 9 PER CENT CHROMIUM STEELS*

Specimen No.	Composition, per cent						Room-temperature properties					Short-time tensile properties at elevated temperature					
	C	Mn	Si	Cr	W	Ni	Tensile strength, lb./sq. in.	Yield strength, lb./sq in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness	Temperature of test °C.	Temperature of test °F.	Tensile strength, lb./sq. in.	Yield strength, lb /sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent
A	0 31	0 65	0 91	7 96	.	20 65	92,000	23,000	36	52	. . .	315	600	94,000	20,000	33	53
												425	800	74,000	18,000	31.5	53
												540	1000	62,500	13,500	34	57
												650	1200	49,500	9,200	39	69
B	0 40	0 59	0 76	7 93	7 70	0 26	110,000	51,500	23 5	56	. . . .	315	600	93,500	34,000	21 5	55
												425	800	84,500	26,000	21	56
												540	1000	62,000	18,000	23	67
												650	1200	37,500	9,500	41	84
C	0.48	0.59	3 54	9 16	.	. . .	135,000	80,000	22.5	46	. . . . .	315	600	114,500	47,500	18.5	43
												425	800	100,000	34,500	20.0	49
												540	1000	63,500	16,000	24 0	73
												650	1200	30,000	4,000	43 0	94

* Clark and White.[210]

TABLE 156.—MECHANICAL PROPERTIES OF 5 TO 6 PER CENT CHROMIUM STEELS CONTAINING COLUMBIUM AND TITANIUM*

Steel No.	Type of steel	Composition, per cent						Air cooled from		Time at temperature	Tensile strength, lb./sq. in.	Yield strength, lb /sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Izod impact, ft-lb.	Erichsen value	Brinell hardness	Rockwell *B* hardness
		C	Mn	Si	Cr	Ti	Cb	°C.	°F.									
1	Cr	0.10	.	...	5.44			As rolled			181,000	149,500	5	12	22	5.5	375	
								750	1380	4 hr	92,500	74,000	26	74	94	7.9	153	
								900	1650	10 min.	.	..	..	.	.	5.5	340	
2	Cr-Ti	0.11	...	....	5.41	0.75	...	As rolled			100,000	84,000	18	68	24	6.3	163	
								750	1380	4 hr.	61,000	28,000	37	78	63	9.0	112	
								900	1650	10 min.	62,000	29,000	44	79	112	9.5	112	
3	Cr-Cb	0.09	...	..	5.62		1.04	As rolled		.	111,000	98,000	16	62	59	6.0	192	
								750	1380	4 hr.	62,000	32,000	29	78	108	8.1	112	
								900	1650	10 min.	82,000	61,000	27	70	105	8.0	143	
4†	Cr-Ti	0.13	0.56	0.39	5.93	0.90	.	As rolled		. .	66,100	39,800	34	68	69	..	128	86
								900	1650	10 min.	67,100	34,200	37	68	74	...	112	63

* Becket and Franks.[414]

† Test pieces for steel 4 from 0.5-in. plates, all others standard test bars from 1-in. round bars.

reduces its loss by oxidation when exposed to elevated temperatures—up to 1000°C. (1830°F.)—that it becomes a useful material for many services which are not too exacting. Columbium when added to these steels also has a favorable effect on the oxidation resistance and, further, tends to reduce the formation of oxides which may become entrapped during welding. Resistance of a series of steels to oxidation at 815°C. (1500°F.) for periods up to 9 weeks was determined at the Union Carbide and Carbon Research Laboratories, Inc. The compositions of the steels used are given in Table 157. The relative oxidation resistance is plotted in Fig. 186. Of the materials containing less than 10 per cent chromium, steel 8 was the most resistant.

TABLE 157.—COMPOSITION OF STEELS USED BY UNION CARBIDE AND CARBON RESEARCH LABORATORIES, INC.

Steel No.	Composition, per cent				
	C	Cr	W	Mo	Ti
1	Carbon steel				
3	0 11	5 49			
6	0 13	5 77			0 90
7	0 13	5 75	1 05		0 91
8	0 07	6 20		0 51	0 74
9	0 06	6 8			0 69
10	0 12	13 17			
12	0 10	16 15			
13	0.24	28 61			

195. Application of Plain and Modified Chromium Steels Containing 4 to 6 Per Cent Chromium.—It is difficult to compare the steels of this group with the highly alloyed corrosion-resisting kind. Of course, the 4 to 6 per cent chromium steels are not stainless, neither do they compare favorably with the higher chromium types in atmospheric-exposure tests. It has been recognized, however, that they are so much better than the plain carbon steels for many specific purposes that they have easily won and maintained their popularity for certain uses, particularly in oil cracking still tubes, valves, fittings, and return bends. Owing to their qualities at high temperatures plus their increased resistance to "sour" oils, the 4 to 6 per cent chromium steels

have as much as four to twenty times the life of carbon steels. Steels in which the chromium is increased to about 8 or 9 per cent have shown such a decided improvement in surface stability, especially when alloyed with 0.6 per cent or more of titanium, as to approach the properties of the so-called stainless steels.

It has been pointed out by both laboratory investigators and users of these steels that the properties of the 4 to 10 per cent

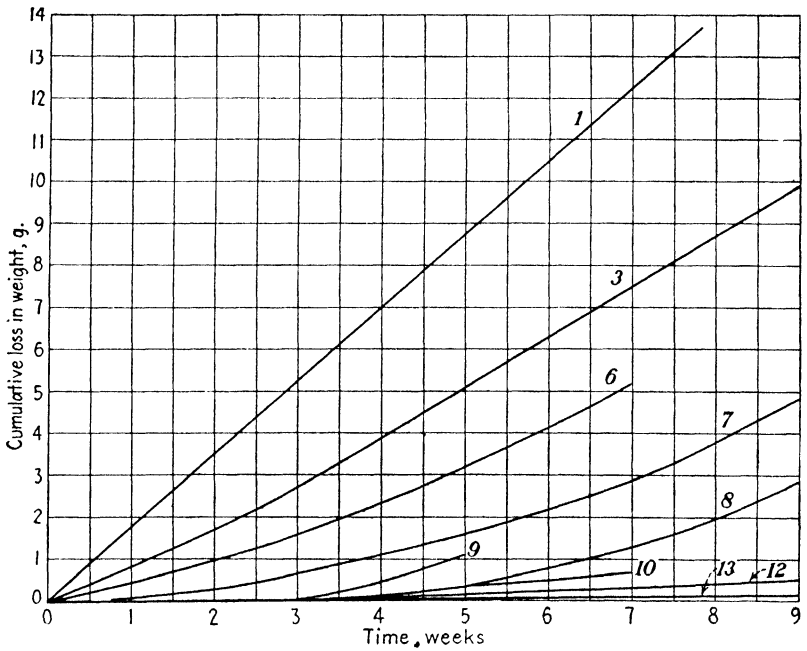


FIG. 186.—Effect of composition on oxidation losses at 815°C. (1500°F.). See Table 157 for composition. (*Union Carbide and Carbon Research Laboratories, Inc.*)

chromium steels change slightly and uniformly with increasing chromium content; the surface stability, however, which increases gradually in this composition range, increases rather sharply at a chromium content of approximately 10 per cent. Oxidation tests on a series of steels with increasing chromium content show[187] a sharp break in the curves at about 10 per cent chromium. In thermal, magnetic, and electric properties this sharp break is not evident.

The 4 to 6 per cent chromium steels, either with or without modification by such additional elements as molybdenum and

tungsten, do not show creep strength notably higher than some pearlitic steels of lower alloy content; nevertheless the fact remains that they are at present the most extensively used steels in the field of high-temperature-pressure work in spite of the fact

TABLE 158.—COMPOSITION AND APPLICATIONS OF MODIFIED CHROMIUM STEELS*

Specimen No.	Composition, per cent								Remarks
	C	Mn	Cr	Ni	W	Si	Mo	Al	
1	0 38 to 0 45	0 30 to 0 60	9 00 to 9 75			3 25 to 3 75			Widely used for automobile-engine valves. Tensile strengths at 710°C (1300°F.) and at 815°C. (1500°F.) are 25,000 and 8500 lb per sq. in., respectively
2	0 40 to 0 50	0 20 to 0 50	8 0 to 9 0	...	0 5 max.	3 00 to 3 50	.		Better wear resistance than average. Good oxidation resistance
3	0 45 to 0 60	0 35 to 0 65	7 0 to 9 0	....	...	1 00 to 2 00			Good for valves where service is not too severe
4	0 46 to 0 52	0 30 to 0 60	10 5 to 11 5	1 25 to 1 50	...	0 90 to 1 10		1 75 to 2 10	May be substituted for No. 1
5	0 35 to 0 50	0 65 max	7 0 to 9 0		1 0 to 2 0	2 75 to 3 75			Excellent resistance to scaling
6	0 47		10 54	1 65		0 83		2 25	Good oxidation resistance to 1010°C (1850°F)
7	0 40		9 0			3 0			For operation up to 760°C (1400°F.). Room-temperature tensile strength, 150,000 lb. per sq in ; elongation in 2 in., 20 to 22 per cent, reduction of area, 60 to 80 per cent
8	0 15		2 50			0 75	0 50		For oil-refinery service. Creep strength (for a rate of 1 per cent elongation in 100,000 hr) at 540°C. (1000°F.), 5500 lb. per sq. in.
9	0 10		5 00			0 40	0 50	.	For oil-refinery service. Creep strength (same rate as for steel 8) at 540°C. (1000°F.), 7000 lb. per sq. in.

* Steels 1 to 6, and 8, Symposium on Effect of Temperature on the Properties of Metals;[310] steel 7 Davis;[316] steel 9 Wilson.[461]

that they are not nearly so corrosion resistant as those of higher chromium analyses. A most important feature of these modified steels is their ability to "hold on" in oil-still service, by slowly expanding with considerable toughness and indicating, at inspection periods, their impending failure in cases where they are overstressed. Some high-temperature properties of these steels are shown in Tables 155 and 158.

196. Applications of Modified Chromium Steels Containing 6 to 10 Per Cent Chromium.—For some time, it has been recognized that the tendency among metallurgical engineers was to develop steels with chromium contents higher than 4 to 6 per cent, for the simple reason that experiments indicated the greater stability of such steels. The results obtained from such experiments are detailed in an article by Newell.[472]

After a number of exploratory heats were studied, the adopted analysis was:

Element	Percentage
Carbon	0 15 maximum
Manganese	0 50 maximum
Silicon	0 50 maximum
Chromium	8 to 10
Molybdenum	1 25 to 1 75

Newell gave data on tensile properties at room and elevated temperatures (both long- and short-time tests), oxidation resistance, workability, susceptibility to embrittlement by tempering treatments, weldability, impact, and heat-treating response. Some of his results are given in Table 159. Creep-strength values of this 9 per cent chromium-molybdenum steel at the respective rates are claimed to be from about one and one-fifth to nearly two times those of the 5 per cent chromium-molybdenum steels.

A predictable result was that molybdenum slightly reduced the oxidation resistance of the steels, but the benefits derived from its stabilizing influence on creep justified its use; oxidation resistance is excellent at temperatures up to 650°C. (1200°F.). This was determined on samples ¾ in. round by 2 in. long, heated for 250 hr. to 650°C. (1200°F.), during which test they were 10 times cooled to room temperature without scale removal, with

final removal of the scale and weight-loss determination. Under these conditions, carbon steel lost more than 9 g., the 9 per cent chromium steel lost less than $\frac{1}{5}$ g., while the 18 per cent chromium, 8 per cent nickel material lost no weight. It is stated that a number of seamless-tube installations are in use in oil refineries. The nominal analysis is 9.25 per cent chromium and 0.12 per cent carbon with or without molybdenum.

TABLE 159.—PROPERTIES OF AN ANNEALED CHROMIUM-MOLYBDENUM STEEL CONTAINING 0.12 PER CENT CARBON, 0.38 PER CENT MANGANESE, 0.09 PER CENT SILICON, 9.42 PER CENT CHROMIUM, AND 1 41 PER CENT MOLYBDENUM*

Property	Testing temperature				
	Room	480°C. (900°F)	540°C. (1000°F.)	595°C. (1100°F)	650°C. (1200°F.)
Tensile strength, lb. per sq. in.	81,500				
Yield strength, lb per sq. in.	41,800				
Elongation in 2 in., per cent	34 5				
Reduction of area, per cent	76 9				
Brinell hardness	143				
Charpy impact, ft-lb	63				
Stress, lb. per sq. in. for creep of:					
0.1 per cent in 1000 hr.		33,250	11,650	6,950	2,300
0.01 per cent in 1000 hr		24,750	5,800	3,775	1,600

* Newell [472]

The preceding remarks apply to steels in the oil-still-tube class in which chromium is the predominating element. There are other classes of chromium steels, important commercially, in which additional elements are present in such amounts that, though they may not actually outweigh the chromium in percentage, they are sufficient to make their effects predominate. Some of the important compositions are given in Table 158.

In the compositions shown, the chromium content is above the 4 to 6 per cent chromium range because of the better surface stability demanded in the given service. Automobile valves are

an important article from the tonnage angle, in this category of steels. One of the compositions most favored in this service approximates 9 per cent chromium and 3 per cent silicon and is usually known under the generic term silchrome. Valves of this material are made either by upsetting rod having the same diameter as that of the valve stem, or by extruding rod having the same diameter as that of the valve head. The tappet end of the valve is then locally hardened by the flame-hardening process. A number of special tool steels, used for dies in die casting and for certain types of hot forming, contain between 4 and 10 per cent chromium, not uncommonly together with small amounts of tungsten, molybdenum, vanadium, and silicon. With these special-purpose tool steels may also be included a modified high-speed steel containing 12 to 16 per cent tungsten, 3 to 4 per cent chromium, and 0.50 to 0.70 per cent carbon. This is used for its wear resistance in certain applications involving temperatures up to 540°C. (1000°F.). This material is mentioned here instead of in Chapter XI, because the service is so different from that normally associated with high-speed steel.

C. AUTHORS' SUMMARY

1. The structure and properties of the 4 to 10 per cent chromium steels, with or without other alloys, are directly in line with the theory as discussed in earlier chapters, and, within limits, the properties might well be predicted from the theory. They require slightly higher normalizing or quenching temperatures and appreciably higher tempering temperatures to achieve the same structure as steels lower in chromium. While some advantage is taken of the increased corrosion resistance as well as oxidation resistance of these steels, they are not in the same category as the higher chromium steels. However, their ease of manufacture, relatively low cost, and excellent physical properties result in their wide application.

2. The 4 to 6 per cent chromium steels, in the lower carbon ranges, with or without molybdenum, tungsten, columbium, or titanium, best meet the needs of moderately-high-temperature service. In the medium-carbon ranges, the wear resistance, afforded by the chromium carbides, and the corrosion resistance, afforded by the chromium-bearing matrix, are valuable attributes in addition to the high mechanical properties, making these

steels particularly useful for dredge parts and parts for similar types of service. In the higher chromium ranges, with or without other alloying additions, the steels exhibit sufficient oxidation resistance, together with their other properties, to warrant application in hot-working dies, poppet valves, and the like.

3. The steels of this category are definitely intermediate in type and may be considered to have the same or better properties than the lower chromium steels and to have a small but important part of the corrosion resistance and oxidation resistance of the next higher bracket of chromium steels.

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