

Chapter III

ALLOYING ELEMENTS IN UNHARDENED STEELS

In many respects the effects of alloying elements are best followed by considering, first, the behaviors of steels carrying various proportions of the several elements as they cool from an elevated temperature and, in so doing, undergo the allotropic transformation and manifest its attendant reactions. Practically, however, there are good reasons for considering first the distribution of the several elements in annealed steels or in steels which have cooled at sufficiently slow rates as to permit the presence generally of constituents which are at substantial equilibrium. One of the most persuasive circumstances urging this latter approach to the subject is the desirability of acquiring as soon as possible a broad, qualitative familiarity with the combining tendencies of the alloying elements; that is, their distribution in steels when the iron is largely in the alpha form and when the carbon is largely combined as a metallic carbide in microscopically sizable masses.

Practically also this order of discussion is more in line with the users' acquaintance with alloy-bearing steel, because most of the steels under discussion are shipped from the steel works to the user in the rolled or annealed condition. Thereafter they are shaped and machined, either to enter service or, more often, to be next heat-treated and finished for service. Furthermore, a considerable tonnage of high strength, low-carbon, alloy structural steel is employed in the as-rolled condition; indeed such steels are intentionally not very responsive to heat-treatment.

Classification of the Constituents in Alloy Steel—In order to discover what the alloying elements may accomplish by their incorporation in the steel it will be helpful to see in

what way they may be distributed in the various constituents which may possibly be present. The first question is, then, what are the possible individual constituents to be found in alloy steel, or more exactly, what phases may exist in annealed steels of various compositions? Referring still to annealed steel there are, first of all, the two metallurgically essential constituents:

1. Ferrite; alpha iron with dissolved elements.
2. Carbide; cementite with dissolved elements or special carbides carrying alloying elements and iron.

In addition, the steels generally carry an exceedingly small amount of nonmetallic material in the form of dispersed particles. These inclusions, in commercial steels, are generally particles of certain mineralogical substances such as complex oxides, sulphides, silicates, etc., which form as the result, primarily, of the greater solubility of oxygen (or sulphur, etc.) at elevated temperatures above the melting point than at lower temperatures. Fortunately, fine dispersions of such nonmetallics serve to prevent excessive grain growth and, unfortunately, they occasionally achieve a particle size of dimensions regarded as undesirable.

There are instances in which a fourth kind of constituent is thought to be present under some circumstances, that is, intermetallic compounds. (In this category might be included the nitrides which, like the carbides, may appear metallic as do the compounds of the metals themselves). In steels discussed here such compounds are exceedingly rare or, at any rate, little known. Finally, a fifth possible constituent is the added element itself, e.g., lead or copper. There being then only five categories of separate entities in the steel, the alloying elements added must be located in one or more of these substances. Strictly speaking, there is probably some solubility for the elements in all phases present but in a practical way the individual elements are each inclined usually to

locate themselves in two or perhaps three of the phases or groups with often a strong preference for only one of them.

DISTRIBUTION OF THE COMMON ELEMENTS IN ANNEALED STEEL

Having in mind at this time only annealed or, at any rate, unhardened steels, we may be certain that considerable opportunity is provided for the alloying elements to locate themselves in accord with their inherent characteristics. This distribution will occur regardless of the precise state of solution previously obtaining in the molten metal. The most important point to bear in mind is that the partition of an element among the several possible constituents depends upon the concentration of other elements. Only the barest trends may be predicted unless the whole composition is known. There are principles, however, which may be broadly applied to specific examples when the analysis is known.

Principles of Distribution — In a nearly pure iron-carbon alloy there may be iron oxide inclusions and these will be present also when elements are added which have little deoxidizing power, i.e., those whose oxides could not exist in the presence of a large amount of iron which would itself seize the oxygen. Manganese, however, would tend to find its way into such oxide inclusions though always remaining in part in the ferrite. Siliceous inclusions form when silicon is present in sufficient amount and finally a stronger deoxidizer, aluminum, would more and more combine with the oxygen as its proportion increased. A small proportion of aluminum would be largely located in the nonmetallic inclusions if oxygen were available, but would be dissolved wholly in ferrite in the absence of oxygen in any form. Silicon might be found almost wholly in ferrite if the oxygen were very low or the previous aluminum addition sufficiently high.

A carbide-forming element such as tungsten may, if present in only moderate amount in a high carbon composition, be found almost wholly in the carbide phase; if it is itself present in high concentration in a low carbon steel it is largely dissolved in ferrite. Such a moderately strong carbide-builder may, however, still be found largely in ferrite in the presence of high carbon if at the same time a large amount of a still stronger carbide-forming element is present. Thus chromium, and to some extent tungsten and molybdenum, are forced into ferrite solid-solution by titanium (or columbium) unless the carbon is sufficient to combine both with most of the titanium and with much of the other less active element.

Some of the elements are not found extensively in the carbide phase, e.g., nickel, aluminum, silicon, copper and cobalt. Thus, although silicon may to a small extent be utilized in combining with oxygen, these elements will all be found largely dissolved in ferrite. Copper, however, having a limited solubility in ferrite will be found in the form of a nearly pure copper (saturated with iron) dispersion of particles when present to an extent of more than about 1 per cent.

It should finally be stressed that no element is wholly located in one single constituent; reactions resulting in a relegation to some phase never complete themselves but stop short of this condition at a real equilibrium. An approach to a complete removal of an element from solid-solution occurs when another element with which it forms a compound, carbide, oxide, etc., is present in great proportion. When the necessary excess is small, then the element is said to have strong combining tendencies as, for example, titanium has a strong carbide-forming tendency.

General Trends in Distribution of the Elements — By way of summary, it may be said that the relative combining

tendencies of the elements may be observed and then stated with definiteness, but that the actual location or distribution in any certain instance depends upon the composition into which an element is introduced and since this constitutes a difficult and complex field of analytical study only trends can be predicted with assurance. Indicating such trends in annealed steel the following table may be taken as a first approximation of the behavior of the individual elements:

	Dissolved in Ferrite	Combined in Carbide	In Nonmetallic Inclusions	Special Intermetallic Compounds	In Elemental State
Nickel	Ni			Ni-Si Compd. (?)	
Silicon	Si		$\text{SiO}_2, \text{MxO}_y$		
Aluminum	Al		Al_2O_3 Etc.	AlxNy	
Zirconium	Zr		ZrO	ZrxNy	
Manganese	Mn \longleftrightarrow	Mn	{ MnS, MnFeO MnO, SiO_2 Cr_xO_y		
Chromium	Cr \longleftrightarrow	Cr			
Tungsten	W \longleftrightarrow	W			
Molybdenum	Mo \longleftrightarrow	Mo			
Vanadium	V \longleftrightarrow	V	V_xO_y	V_xNy	
Titanium	Ti \longleftrightarrow	Ti	Ti_xO_y	{ Ti_xNyC_z Ti_xNy	
Phosphorus	P				
Sulphur	S (?)		{ MnFeS ZrS		
Copper	Cu				Cu when > $\pm 0.8\%$
Lead					Pb (?)

In the absence of carbon very considerable proportions of the usually added metallic elements, other than lead and copper (in excess of some 0.8 per cent) will be found dissolved in the ferrite, except there be a small proportion accounted for in the nonmetallic inclusions. Clearly the carbide-forming tendency of the elements is manifest only in the presence of a significant proportion of carbon. The relative carbide-forming tendency of the several elements in steel is of greater importance at elevated temperature at which a considerable proportion of carbon is in solution in austenite; nevertheless the elements can be arranged in an order which will indicate their relative activity in combining with carbon at the low range of temperature and these characteristics are

also important. The case is somewhat complicated by the fact that iron carbide in pure iron-carbon alloys is itself either unstable or an exceedingly weak compound at temperatures below about 715 degrees Cent. Hence the presence of elements of still lower carbide-forming tendency (than iron) merely promotes the formation of graphite, e.g., nickel and silicon. In most commercial steels, however, there is sufficient manganese to prevent the formation of graphite in ordinary operations. Of the definitely carbide-forming elements manganese is perhaps the weakest. In steels carrying some 10 per cent manganese, when rendered ferritic, the manganese-iron ratio in the carbide is some 1:4 instead of 1:9 as in the steel as a whole. In a 1.0 per cent carbon steel with 10 per cent chromium, the ratio of chromium to iron in the carbide would probably be somewhere in the vicinity of 4:6 instead of the nearly 1:9 ratio in the steel as a whole. It is inferred indirectly that the carbide-forming tendencies of the elements would place them in about the following order of increasing intensity,—manganese, chromium, molybdenum, tungsten, tantalum, vanadium, columbium, titanium. Those having less tendency than iron has to combine as carbide in steel are silicon, aluminum, copper, nickel, cobalt and possibly zirconium. The position of molybdenum is uncertain.

The carbide phase in carbon or low-alloy steel is of the orthorhombic cementite crystal form, and in the presence of small amounts of carbide-forming elements the alloying elements are able to be accommodated to a limited extent in this crystal by replacing iron. A condition is soon reached, however, with increasing proportion of a carbide-forming alloy, in which cementite no longer accommodates additional foreign atoms and a new carbide crystal lattice is formed. Usually there is a minimum proportion of alloying element in the special carbide which considerably exceeds the maximum soluble in cementite and accordingly the two varieties

of carbide exist together in some compositions. It will be understood that the special carbide will make its appearance at a lower alloy content in low-carbon steel than in high-carbon compositions.

Having in mind the broad classification of the elements as they are individually partitioned between the ferrite and the carbide phases in the ferrite-carbide aggregates of steel, it will be of interest to consider the effects of the presence of the individual elements in these two principal constituents

EFFECTS OF THE ALLOYING ELEMENTS UPON FERRITE

The effect of increasing concentrations of the elements upon the mechanical and other physical properties of ferrite may be studied directly by investigating substantially carbon-free alloys. The same basic effect may be observed in a carbon-bearing series also, provided only that the volume, distribution and particle size of the carbide particles remain constant. This uniformity may be difficult experimentally to achieve and it may be exceedingly difficult in some cases to know the precise composition of the ferrite separately. Nevertheless, such information is of great practical value in building up a basis for understanding alloy effects and accordingly the comparable conditions have been at least closely approached in some experimental investigations to be reported here. So far as is known, any element dissolved in ferrite increases its hardness and strength in accord with the general rule of solid-solution.

Solid-Solution Hardening Effect in Pure Iron — Surprisingly little is known of the effects of the individual elements dissolved in ferrite and this includes even hardness and tensile properties. Not only are the data confused by grain size variations but by more than traces of sundry elements present in some of the series studied. With respect to hardness, which is an informative indication of the solid-solution effect

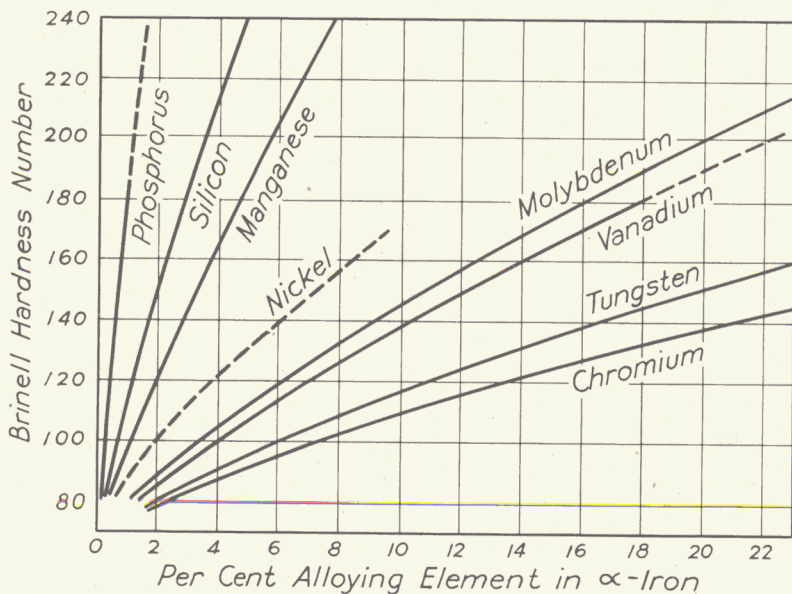


Fig. 40—Probable Hardening Effects of the Various Elements as Dissolved in Pure Iron.

to strengthen the iron, the meager data have been assembled and carefully considered as to the most probable values and are presented in Fig. 40.⁴ The order of increasing effectiveness based upon equal additions by weight appears to be about as follows: chromium, tungsten, vanadium, molybdenum, nickel, manganese, silicon, phosphorus. A fairly coarse grain size is assumed for all compositions and the hardness of pure iron is considered to be 70 B.H.N., a figure representative of the purest varieties of thoroughly commercial, annealed iron. The hardness of solid-solutions of several of the elements in iron is shown for compositions which are not stable ferrite under all conditions. This is possible because the ferrite remains unchanged at room temperature even though unstable.

The hardening effect of the elements in solid-solution

⁴The author gratefully acknowledges the information received in private communications from A. A. Bates, G. R. Brophy, A. J. Herzig, R. F. Mehl and W. P. Sykes and employed in estimating the position of the curves in Fig. 40.

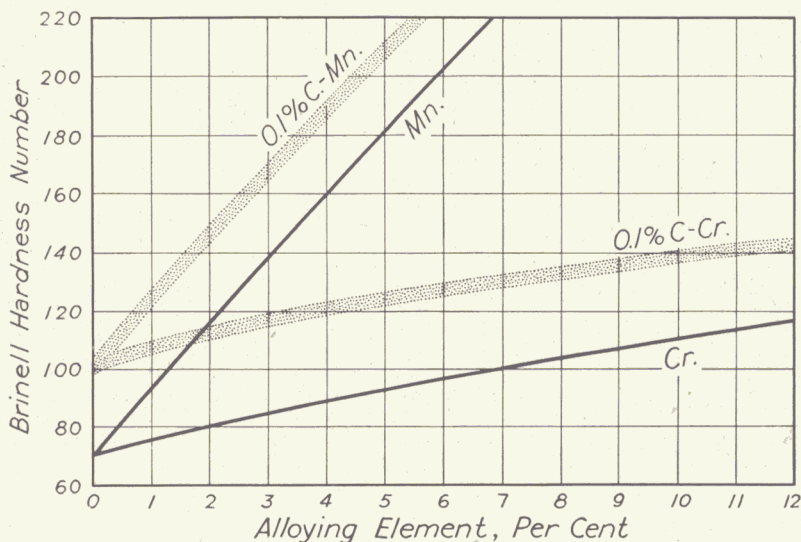


Fig. 41—Hardness Increase caused by Chromium and Manganese as Dissolved in Ferrite. Bands indicate Annealed 0.1 Per Cent Carbon Steels; Lines refer to Substantially Pure Iron Alloys.

may seem surprisingly small but this is probably due to the unfamiliarity with the carbon-free alloys of iron. At any rate, the chart serves to indicate how relatively little of the over-all contribution of alloying elements in steel is due to the strengthening of ferrite. A dispersion of a relatively small aggregate mass of fine particles may strengthen a metal such as iron far more than a much larger proportion of dissolved element but in so doing it generally exacts a far greater loss in plasticity.

Solid-Solution Hardening in the Presence of Carbide—

In the presence of a small proportion of carbon, for example, about 0.1 per cent, the increase in strength is still due mainly to the solid-solution effect of the element in ferrite, provided the metal has been annealed or so slowly cooled as to allow the carbide to form in moderately sizable particles. Thus in a series of 0.1 per cent carbon, chromium steels the hardness

follows substantially the course shown by the broadened band in Fig. 41, with which, for comparison, is shown the probable hardening effect of chromium in substantially carbon-free iron. It should be noted that an unusually extended scale for Brinell hardness is employed. In the same diagram the hardness of thoroughly annealed manganese steels with 0.1 per cent carbon is also shown along with the probable hardness of carbon-free ferrite in iron-manganese alloys. Since the data are not as precise nor as plentiful as might be desired, the hardness for the 0.1 per cent carbon alloys is shown as a band; the most probable values, however, are employed and the relatively moderate hardening would be expected from the solid-solution effect alone. It will be understood that the more thorough the annealing the smaller will be the total hardening effect contributed by carbide particles and that, therefore, the series of hardness numbers plotted will then more nearly represent the solid-solution effect of the alloying element. Furthermore, any difference in this effect from one alloy content to another will likewise be at a minimum when the total effect is uniformly low.

It will be especially informative to consider the solid-solution hardening effect in ferrite of an element such as manganese in the presence of still higher carbon. To isolate this solid-solution effect alone, it is necessary to insure that the structure itself is constant over a range of alloy content. By "structure" is meant the fineness, form and volume of the carbide dispersion. This uniformity has been realized in a series of 0.55 per cent carbon steels and an essentially constant structure like that shown in the photomicrograph of Fig. 42 was actually developed in a series of manganese contents ranging up to about 6 per cent. Fig. 43 shows the effect of manganese upon hardness and tensile properties in a lamellar or pearlitic series of 0.55 per cent carbon steels, the only significant structural difference being a trace of free, pro-

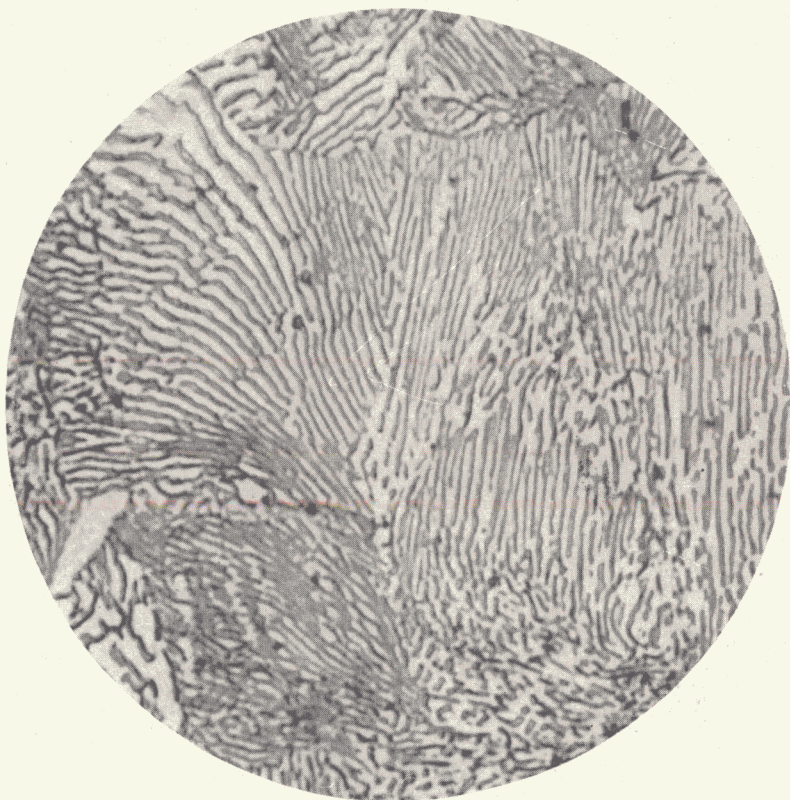


Fig. 42—Microstructure Developed Uniformly in a Series of 0.55 Per Cent Carbon Steels to Evaluate Dissolved Manganese Effect; (1500 \times). (*E. L. Roff*).

eutectoid ferrite in the 0.50 per cent manganese composition. It will be noted that the manganese over the range up to 6 per cent contrives to increase the Brinell hardness only from about 200 to 280. The moderate strengthening effect is accompanied by a considerable loss in tensile elongation (ductility), — an effect which manganese seems to exert even in unhardened steel when present to the extent of a few per cent. It may be of interest to note that the structure selected, (being a lamellar one of medium spacing) was achieved in the ordinary steel by simple air-cooling of a $\frac{1}{2}$ -inch section,

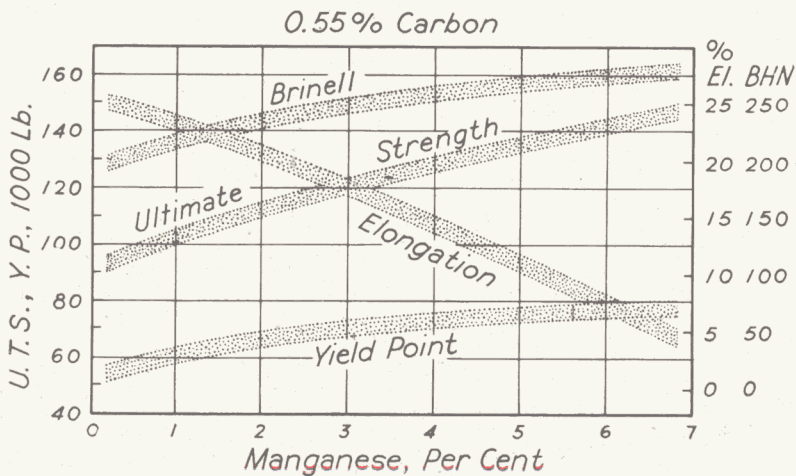


Fig. 43—Effect of Dissolved Manganese in Strengthening the Ferrite of a 0.55 Per Cent Carbon Series of Uniform, Lamellar Structure, as in Fig. 42.

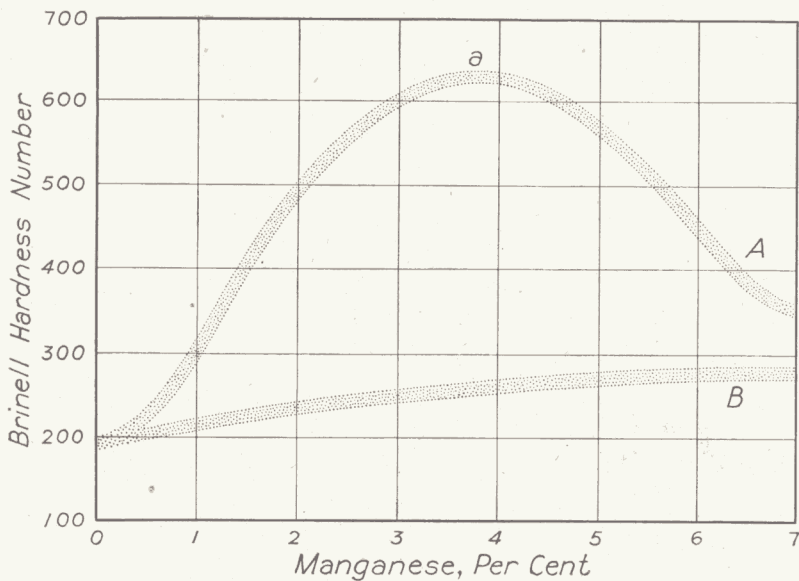


Fig. 44—Effect of Manganese (Curve A) upon the Hardness of 0.55 Per Cent Carbon Steels when Identically Cooled from the Austenitic Condition. (B indicates Constant Structure).

while the higher manganese steel must needs be held for a matter of days at a predetermined temperature to induce the corresponding lamellar structure to form. When, instead of securing a uniform structure a constant heat-treatment is applied, the properties are vastly more affected by manganese. Fig. 44 shows the hardness for the manganese series with a constant cooling rate ($\frac{1}{2}$ -inch rounds in air).

Constant Heat-Treatment versus Constant Structure—

The noteworthy feature of this demonstration is clearly the small effect of an alloying element when it acts only as a dissolved element in ferrite, the structure being substantially constant. Manganese is the ideal element to employ for this experimental study since it permits the same mode of transformation (however different the rate) in the several compositions and does not much alter the volume of carbide, as do some other elements which induce special carbides. One may properly conclude that if the only effect of alloying elements were that of strengthening the ferrite by solid-solution there would be far less interest in them than there is, for this effect is clearly relatively small. Notwithstanding, it will be seen subsequently that in certain steels upon which exacting restrictions are placed, this mild effect is the principal one relied upon to improve the ordinary mechanical properties.

As a further example⁵ of the minor effect of elements dissolved in ferrite, Fig. 45 shows the tensile strength of low carbon (0.10, 0.20 and 0.30 per cent) chromium alloys, both as annealed (furnace cooled) to produce a coarse ineffective carbide distribution and as cooled (in the form of approximately $\frac{11}{16}$ -inch rounds) in air. The difference in the strength of the two series of compositions is a measure of the effect of increasing chromium as it alters *structure* in a constant heat-treatment. In short, the upper curves indicate the normal

⁵“Properties of Low-carbon, Medium-chromium Steels of the Air-hardening Type”, by E. C. Wright and P. F. Mumma, 1933, Technical Publication, American Institute of Mining and Metallurgical Engineers, No. 496, Iron and Steel Division, No. 94.

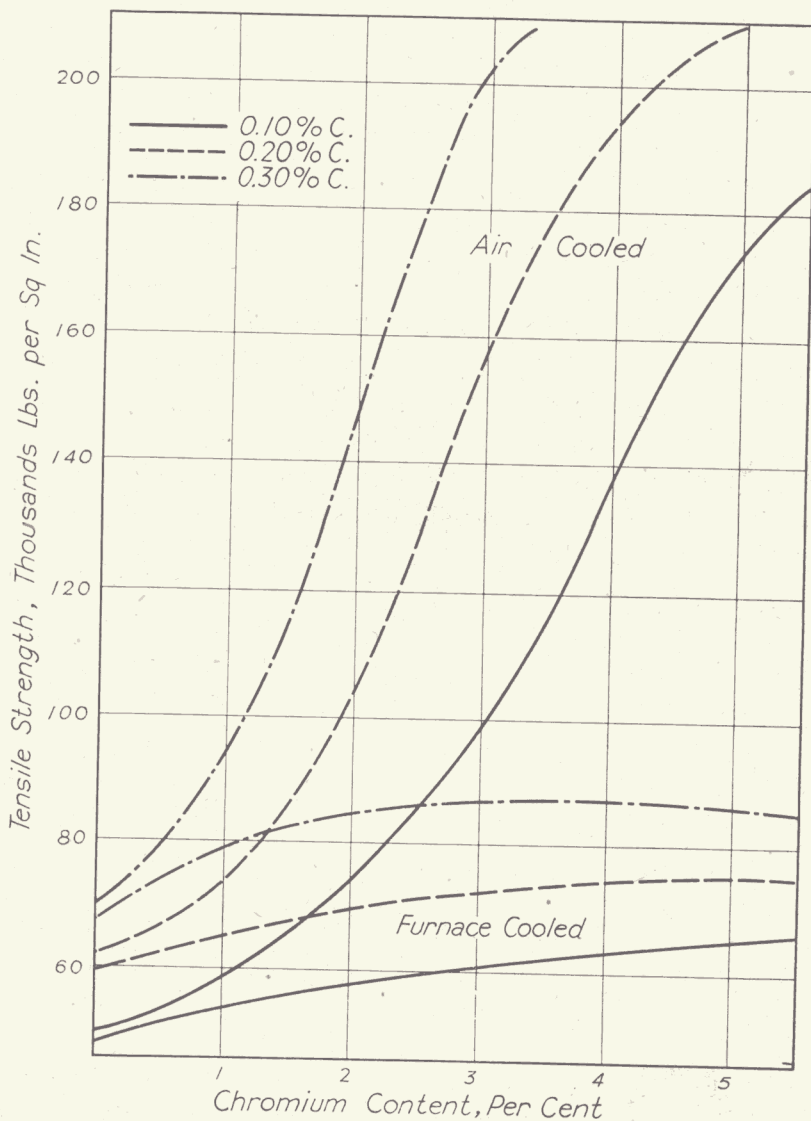


Fig. 45*—The Minor Effect of Chromium in Slowly Cooled Steels Compared with its Strong Effect as a Strengthener through its Influence upon Structure in Normally Cooled Steels. (From Data of Wright and Mumma⁵).

influence of an alloying element to change properties exerted in a *uniform* treatment and variable structure, while the lower curves show the minor effect of an alloying element in essentially constant structures of low hardening influence.

Individuality of the Elements in Ferrite — Thus far the influence of elements dissolved in ferrite has been restricted to hardness and tensile properties at room temperature. Had the testing temperature been higher the apparent effect would in some instances have been greater, though here again the existing data are meager. More regrettable, however, is the lack of information on iron solid-solutions with respect to other mechanical properties. Specially significant would be measures of the effect of dissolved elements upon plasticity under the adverse conditions of notches, not, perhaps, such severe notches as are employed in the Charpy or Izod tests, but of sufficient severity to be of wide engineering significance. Interest would also center in the extent to which continued deformation by simple shear could be endured by the different ferrites as exemplified, for example, in the torsion test. Ideally, one would be in an advanced position in predicting the behavior of low-carbon alloys if only the ultimate cohesive strength or cohesivity accompanying increasing alloying elements were known at various temperatures along with the elastic limit in shear for the same compositions and conditions. At present, however, methods which are practical to apply are lacking for such determinations, particularly for determining cohesivity.

The response of ferrite to different modes of loading, as modified by dissolved elements, is of necessity a dominant factor in low-carbon steels in which such carbon as exists may be spheroidized or dispersed in the relatively ineffective manner of small clusters of pearlite. Indeed the behavior of such steels may be regarded as reflecting mainly the characteristics of ferrite. On this basis one may surmise that the

strengthening by nickel incurs less loss of initial capacity to flow in shear than does comparable strengthening by manganese, silicon or phosphorus, with chromium in an intermediate position at proportions under some 2 per cent. This may mean that the raising of the elastic limit in shear is lower, with reference to increase in absolute cohesivity, in the case of some elements than in others. The order of the elements certainly cannot be stated with accuracy at the present time on the basis of published information. The other interesting behavior, i.e., capacity for continued flow under plastic deformation, relates to the alteration of properties with increased deformation, and seemingly little systematic work has been done on this question. There is no reason that the elements should all behave similarly with respect to their relative alteration of these several fundamental characteristics of deformation under various modes of loading, and it is almost certain that they are dissimilar in these respects.

EFFECTS OF THE ELEMENTS UPON CARBIDE

The second of the two primary constituents in unhardened steel is the carbide phase. We have seen how the amount of carbide, depending upon the proportion of carbon, alters the properties of the steel and how, still more profoundly, the form and fineness of the dispersion of carbide particles influences properties. These broad observations hold in principle for alloy steels as well as for carbon steels, and there have already been seen several examples of these effects in the compositions discussed. As a matter of fact, it would appear that in a given matrix of ferrite, having any certain composition, the room-temperature mechanical properties are very similarly influenced by similar dispersions of hard particles regardless of the composition of the dispersed phase.

Cementite and the Special Carbides — All carbides

found in steel are brittle and relatively so hard that it would be most surprising if such properties as are reflected in the tensile test were much influenced by the specific composition of the carbide. When some of the carbide particles are large and act to resist abrasion, specific properties are brought into consideration and it would be anticipated that special carbides would act differently from ordinary iron carbide; this is indeed true. There are certain tendencies toward form and size which are characteristic of certain carbides. Some, as will be shown, coalesce much less rapidly than iron carbide and these associated properties of the carbide are significant in influencing the nature of the steel. All in all, one may say that similar dispersions of various types and compositions of carbide are not very unlike one another in their effect upon many of the room-temperature tensile properties of steel but that special properties may be contributed by special carbides and that changes in composition of the carbide phase are therefore of interest.

The carbide is little modified by nickel, silicon or aluminum except that graphitization is accelerated in their presence if little or no carbide-forming elements are present. Manganese, chromium, molybdenum, tungsten, tantalum, vanadium, columbium and titanium are the carbide-forming elements and, approximately in the order named, tend more and more to be located in the carbide phase, insofar as the carbon is in sufficient proportion to combine therewith.

With the exception of manganese, which is only moderately more of a carbide-forming element than iron, only a small proportion of the elements are acceptable in the cementite or Fe_3C carbide crystal. This circumstance does not, however, operate to limit the proportion of the element in the carbide phase. On the contrary a new complex carbide is inaugurated by the alloying element which contains a considerably higher proportion of the element.

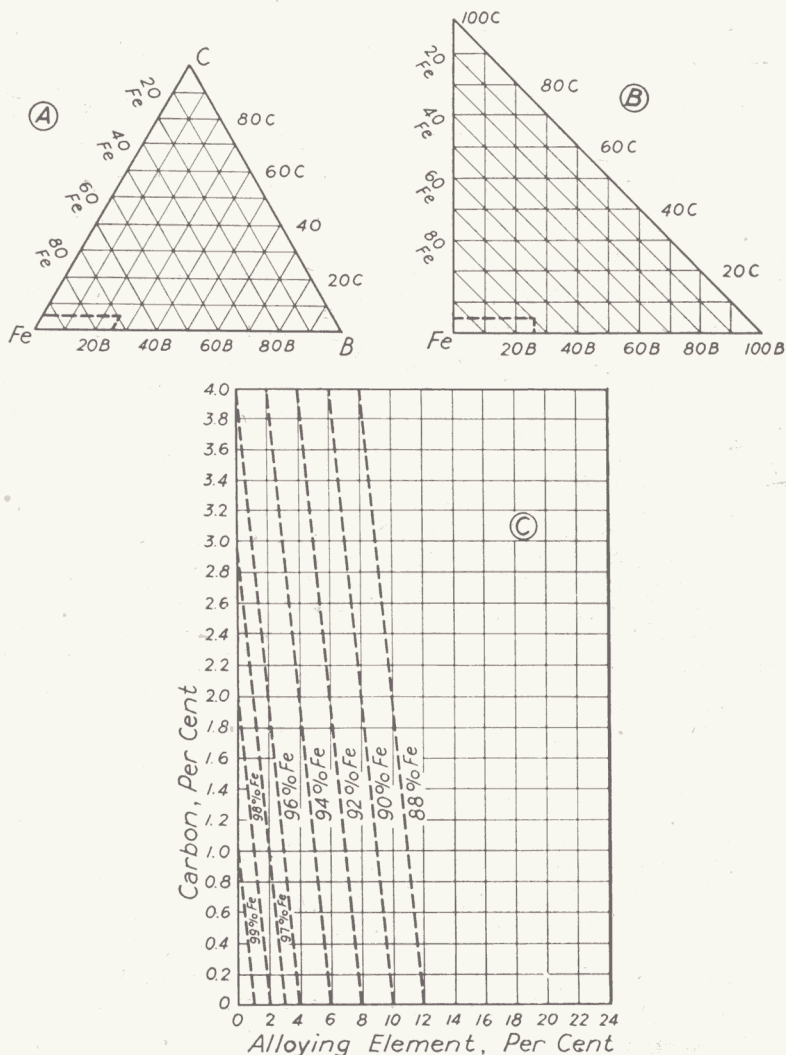


Fig. 46—Development of the Rectangular 3-Component Diagram from the Equilateral Triangular Diagram.

The compositions which result, upon annealing, in a mixture of ferrite and the several possible carbide phases are most easily set forth in diagrams. It is quite possible to represent the composition of a three-component system, as for example, iron, carbon and an alloying element on a two-dimen-

sional plot.⁶ The reason for this circumstance is that only the per cent content of two of the components may be independent; the other must always be the difference between 100 and the sum of the other two. The composition of three component alloys is most lucidly plotted on the equilateral triangular diagram originally employed by Willard Gibbs. As illustrated in Fig. 46-A, the concentration of any one component is represented by the vertical distance from the appropriate side. Thus the three corners represent 100 per cent of each of the components, while the sides constitute the three possible binaries. It will be recalled that the sum of the vertical distances from any point to the sides of an equilateral triangle is a constant. In this diagram, the actual distance on the chart for equal changes in composition is constant over the whole diagram for all components.

If the triangle is distorted to produce, for example, a right-angled triangle, as in Fig. 46-B, most of the usefulness of the diagram is still preserved. The actual distance for a given change in the concentration of any of the three components is not now a constant. The distance representing 10 per cent iron is not the same as that for 10 per cent of B or C. This is a minor disadvantage.

Often it is desired to present in a constitution diagram a detailed account of the influences of one of the components when it is present in amounts far smaller than that of the other two. Carbon is so effective in changing constitution in the ternary iron-carbon alloys that it would be desirable to have an extended scale for it in the diagram. The situation is shown by the area in Figs. 46-A and 46-B set off by dotted lines near the Fe corner. There is no difficulty in arranging this either. Fig. 46-C shows this part of the ternary diagram extended in rectangular co-ordinates for carbon and the alloying element, B, at quite different scales. The iron content

⁶See also footnote No. 11.

may always be arrived at by difference, and its co-ordinates are shown as dotted lines in Fig. 46-C.

This form of diagram will be employed to set forth all the ternary constitutions henceforth. The data have been gathered from the various sources⁷ available and have been considered and drawn to indicate the most probable conditions, according to the author's judgment.

Chromium in Carbides—Fig. 47 shows the several carbide phases which may be encountered in chromium steels, according to composition, when they are well annealed. Annealing in this case means definitely an adequate period at the lowest temperature at which carbon and chromium have diffusivity sufficient to permit the formation of the most stable compounds. The carbides are as follows:

Carbide 1. Orthorhombic Cementite $(\text{Fe.Cr})_3\text{C}$.

May contain up to 15% Cr.

Carbide 2. Trigonal $(\text{Cr.Fe})_7\text{C}_3$.

Contains a minimum of 36% Cr.

Carbide 3. Cubic $(\text{Cr.Fe})_4\text{C}$.

Contains a minimum of 70% Cr.

Under some circumstances a compound FeCr may appear in low carbon alloys containing about 20 to 50 per cent chromium (or higher chromium if much of the chromium is combined with carbon). Stainless steels involve primarily the cubic $(\text{Cr.Fe})_4\text{C}$ carbide.

⁷For the several diagrams showing constitution at equilibrium in the various ternary alloys the data have been drawn chiefly from the following sources:

For chromium; "Das System Eisen-Chrom-Chromkarbid-Zementit", by Tofaute, Küttner and Büttinghaus, *Archiv für das Eisenhüttenwesen*, Vol. 9, 1936.

For tungsten; "Metallographic Investigation of the Ternary Alloys of the Iron-Tungsten-Carbon System", by Shuzo Takedo, Technical Publication, Tohoku, Vol. 9, 1930.

For molybdenum; "The Iron-Carbon-Molybdenum System", by Takesi Takei. English Translation through courtesy of the Climax Molybdenum Corp.

For vanadium; "Ueber das Ternäre System Eisen-Kohlenstoff-Vanadin", by R. Vogel and E. Martin, *Archiv für das Eisenhüttenwesen*, Vol. 4, 1930-31, p. 487.

For titanium; "Das System Eisen-Eisentanid-Titankarbid-Zementit", by W. Tofaute and A. Büttinghaus, May 1938, *Technische Mitteilungen*, Krupp, Vol. 4, p. 67.

For manganese; "The Equilibrium Diagram of Iron-Manganese-Carbon Alloys of Commercial Purity", by E. C. Bain, E. S. Davenport and W. S. N. Waring, American Institute of Mining and Metallurgical Engineers, Iron and Steel Division, 1932, Vol. 100, p. 228.

"Constitution of Iron-Manganese-Carbon Alloys", by Cyril Wells, *Metals Handbook*, American Society for Metals, 1936, p. 290.

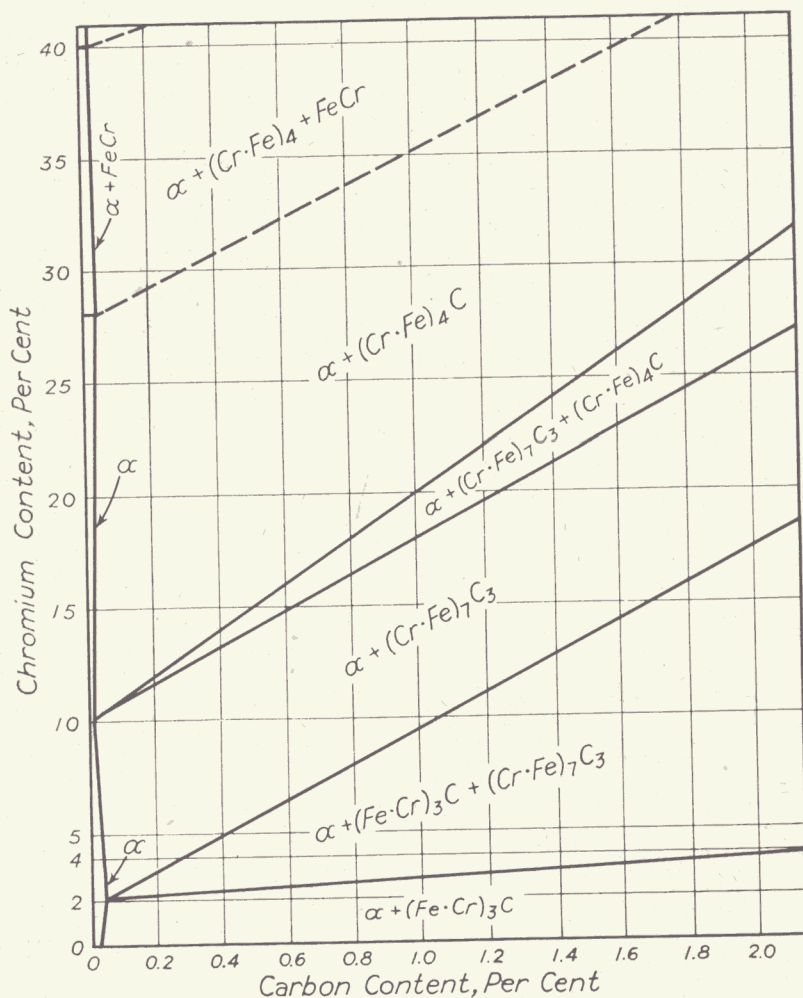


Fig. 47—Constitution Diagram for the Iron-Carbon-Chromium Alloys of Usual Composition Range as Annealed. (Tofaute, Küttner and Büttlinghaus).

Molybdenum in Carbides—Similarly to the annealed chromium alloys, the occurrence of a special carbide in the annealed molybdenum-carbon alloys is shown in Fig. 48. In the ordinary ranges of composition only one special carbide, $(\text{Fe} \cdot \text{Mo})_6\text{C}$, or about $\text{Fe}_7\text{Mo}_5\text{C}_2$ in proportion, is encountered,

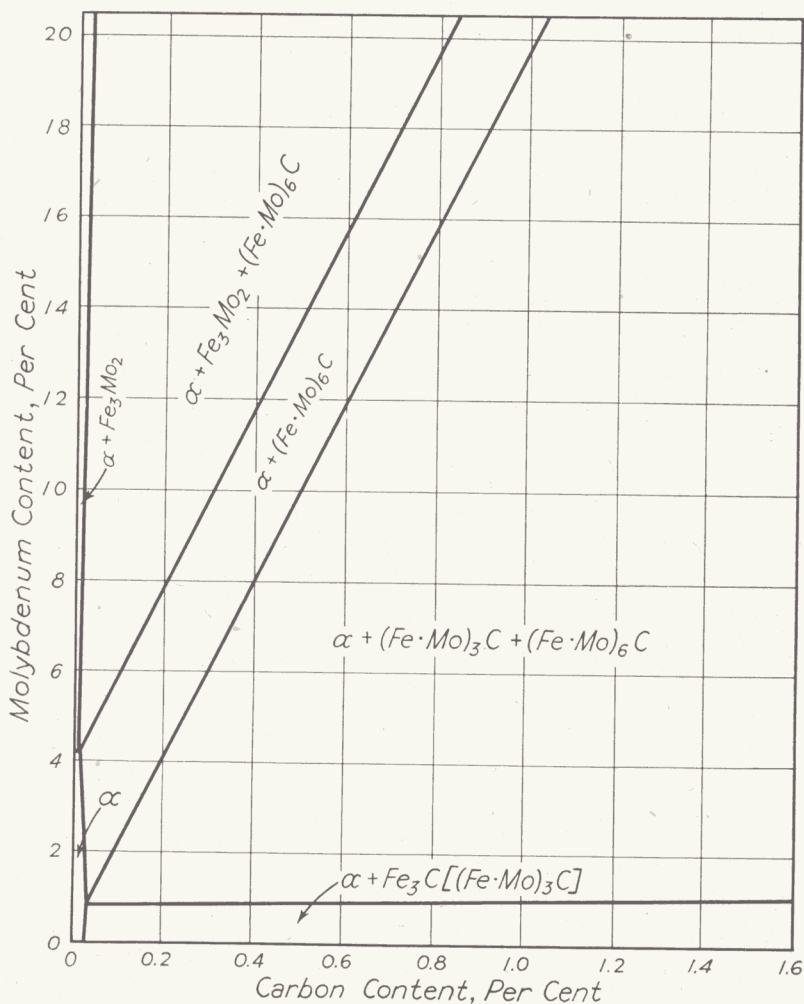


Fig. 48—Constitution Diagram for the Iron-Carbon-Molybdenum Alloys of Usual Composition Range as Annealed. (*Takei*).

but the iron-molybdenum compound, Fe_3Mo_2 , is thought to be able to dissolve some 0.1 per cent carbon and is the compound precipitated in the low-carbon age-hardening FeMo alloys.

Tungsten in Carbides — Fig. 49 shows how exceedingly similar to the iron-molybdenum-carbon system is that of iron-

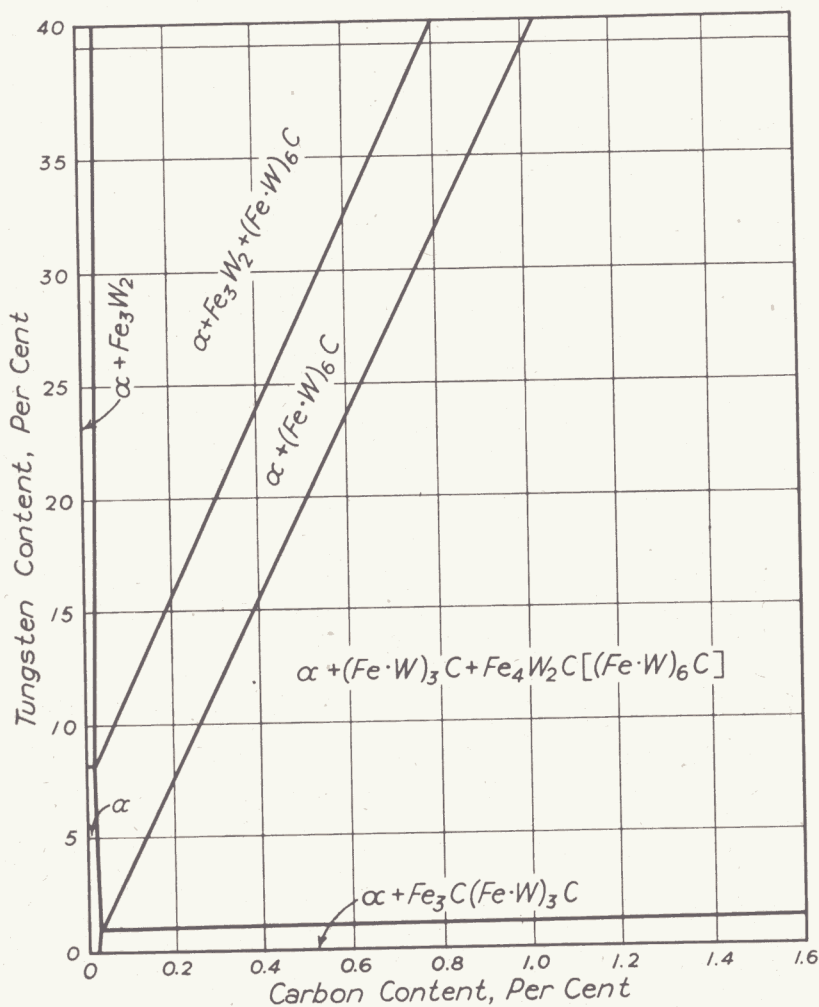


Fig. 49—Constitution Diagram for the Iron-Carbon-Tungsten Alloys of Usual Composition Range as Annealed. (Takedo).

tungsten-carbon except for the actual weight proportion of tungsten. The carbide $(\text{Fe}\cdot\text{W})_6\text{C}$, or approximately $\text{Fe}_7\text{W}_5\text{C}_2$ in proportion, is the one primarily involved in high speed steel. It will be noted that in the absence of the usual chromium and vanadium in high speed steel (both of which prob-

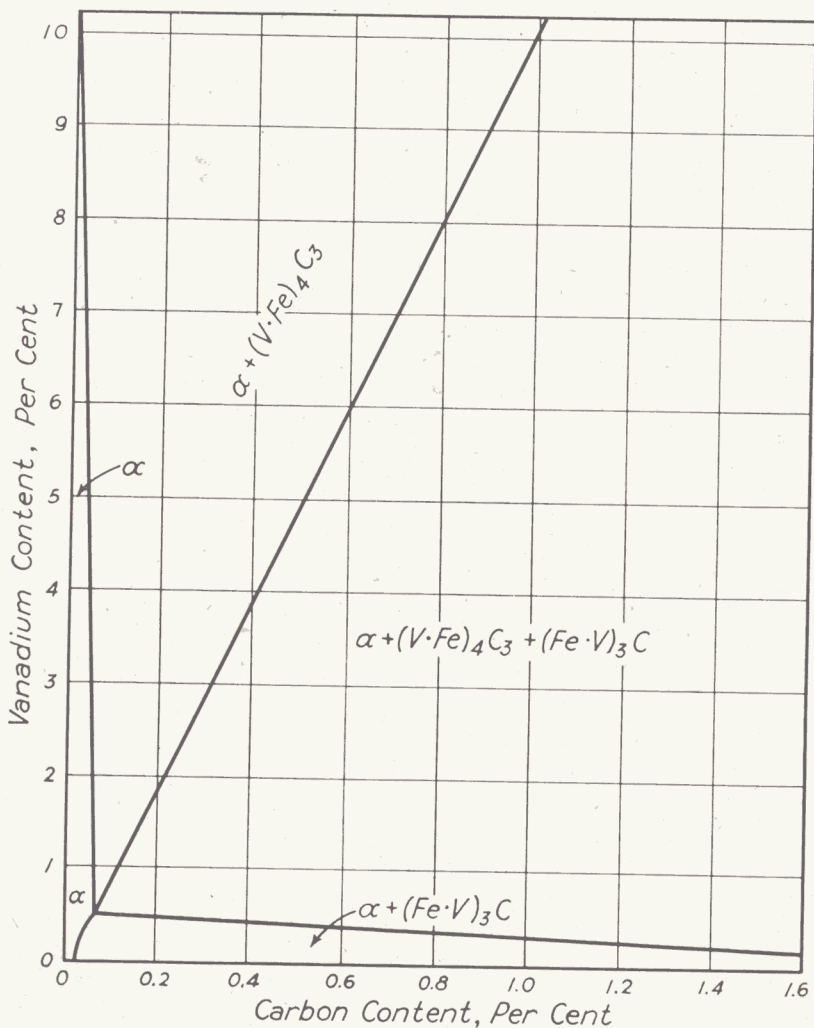


Fig. 50—Constitution Diagram for the Iron-Carbon-Vanadium Alloys of Usual Composition Range as Annealed. (Vogel and Martin).

ably dissolve in the carbide, replacing iron) some small amount of cementite carbide particles $(Fe.W)_3C$ would be involved, according to the diagram, for 18 per cent tungsten.

Vanadium in Carbides — The diagram for iron, vana-

dium and carbon, Fig. 50, shows how the constitution is simplified by the absence of intermetallic compounds of iron and vanadium (corresponding to FeCr and Fe_3W_2 or Fe_3Mo_2) although vanadium in fairly high proportion introduces a special carbide $(\text{V.Fe})_4\text{C}_3$. Although Vogel and Martin indicate a considerable solubility of carbon in vanadium-bearing ferrite and also of vanadium in cementite, the writer's impression is that even the diagram of Fig. 50 may indicate a slightly too high value for these solubilities. The question might be very difficult to answer convincingly.

Special Carbides in Annealed Alloy Steel—Summary—

Summarizing the effect of alloying elements exerted through their combination with the carbide phase, it should first be stressed that such very hard particles as any of the carbides must in similar types of dispersion act similarly in a broad way, with, however, differences in abrasion resistance. With respect to their tendencies to form in differently shaped particles, the result is generally quite as would be anticipated. The main differences among the carbides relate to their differences in volume at the same content of carbon and in the rate of particle growth, a subject reserved for a further chapter on the tempering of alloyed steels.

EFFECTS OF ELEMENTS IN NONMETALLIC INCLUSIONS

From the broad standpoint of enumerating the influences of elements, other than iron and carbon, in steel, the role of nonmetallic inclusions cannot be ignored. At the same time it is not ordinarily customary to think of the formation of nonmetallic particles in steel as an end in itself, to which the ordinary alloying elements are employed. On the contrary, it is more usual to regard as alloyed, only the amount of some added element which is in excess of that used up in the formation of nonmetallics, such as, for example, oxides in deoxidation. Elements in nonmetallic inclusions are considered here,

however, because our interest includes any effects of added elements.

In a general way, very large, nonmetallic inclusions of whatever sort are undesirable, while very fine dispersions are probably of little consequence except in special instances. Clusters of alumina may be noticeably abrasive to cutting tools if unusually prevalent even though fairly fine. The notch effect of "ribbons" or "strings" of siliceous inclusions, especially under transverse load, has been amply pointed out in many publications. Modern demands would scarcely be met by soft steel carrying the volume percentage of non-metallic inclusions such as characterized wrought iron, highly regarded for reliability at one time. The same is probably true of the cemented or blister steel made for tools from the same wrought irons.

Nonmetallic Inclusions and Machinability—By far the greatest interest in nonmetallic inclusions has to do with the improvement of machinability in unhardened steel through the judicious introduction of a dispersion of manganese sulphide in the form of small strings of particles, as in high-sulphur screw-stock. The fundamentals of good machinability are not simple; the conditions under which the cutting is done unquestionably alter the qualifications of the metal to be shaped. A few restricted generalizations may, however, be made, and they explain at least in part how the introduction of certain elements improves machinability.

In a sense good machinability is opposed to most good mechanical properties desired in service. High strength and maximum toughness are very often needed in service, while in essence good machinability appears to depend upon the absence of both, but especially toughness. Considering machinability as involving rapid removal of metal, long tool life between grindings and a good surface on the part, it appears that it is achieved by low ductility, i.e., small capacity

for flow under shear and, if possible, not too high resistance to shear. At the risk of over-simplification it may be said that as low a hardness should be provided as will, at the same time, not be accompanied by high ductility or plasticity. Thus the reduction of area in the tensile test seems to be a factor somewhat applicable to machinability measures.

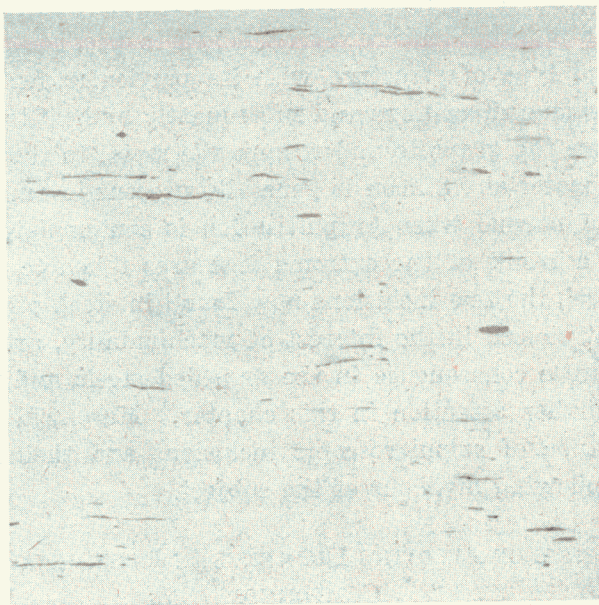


Fig. 51—Photomicrograph showing Inclusions of Manganese-Rich Sulphide; (100 \times). (Courtesy R. W. Simon, Carnegie-Illinois Steel Corporation).

At any rate, it is not surprising that rows of elongated sulphide inclusions would act as miniature notches to aid in “breaking” off chips of metal by shear. The inclusions are most effective in certain directions of machining in relation to the rolling direction, and the final properties are of course least impaired in the case of longitudinal loading. Fig. 51 shows the microstructure of a typical free-machining steel with the inclusions resulting from 0.9 per cent manganese and 0.25 per cent sulphur.

Graphite may be properly regarded as a nonmetallic inclusion when found in steel. In former times when low-manganese (indeed very low-alloy) carbon tool steels were not uncommonly made, steels from some sources were prone to graphitize when treated under certain conditions now known to represent the optimum for carbide decomposition. Although this undesired graphitization is now rare, the same principle may be deliberately employed to produce the malleableized type of structure with its particular features in high carbon compositions and subsequently by heat-treatment to remove the graphite and restore the metal to the carbide type of material. Silicon is generally present in amounts in excess of normal when graphitization is contemplated.

As a result of the extreme measures taken to produce clean steel, the few inclusions now found in steel, other than those introduced in the interest of machinability, are of relatively little consequence in the annealed steels and are not given further attention in this chapter. More will be said of one type of submicroscopic inclusions and their control in the following divisions of the subject.

EFFECTS OF ALLOYING ELEMENTS IN INTERMETALLIC COMPOUNDS

It was necessary to restrict the fields of enquiry for the present purposes and to confine attention principally to the lower alloy steels, with medium carbon content. In these families of alloy steels intermetallic compounds are not thought to form to significant extent although, under some circumstances, they may do so for all one can prove to the contrary. Thus Cox⁸ refers to the possibility of a nickel-aluminum compound occurring in appropriate compositions. Although there appears to be such a compound in the cast

⁸Discussion of paper "Some Characteristics Common to Carbon and Alloy Steels", by E. C. Bain. Yearbook, American Iron and Steel Institute, 1934, p. 123.

carbon-free permanent magnet compositions with nearly 25 per cent nickel and about 10 per cent aluminum, there is probably no compound formed in low percentages of these elements. Nickel and silicon may form a similar system with iron.

In high-alloy iron alloys, compound-formation and age-hardening systems are by no means uncommon. Fe-Ti, Fe-W, Fe-Mo, Fe-Be alloys all develop compounds which are adapted to age-hardening, while even the Fe-Cr system contains a hard brittle compound, the mode of formation of which, however, is not very well adapted to the control needed in a useful age-hardening composition.

Nitrides Possibly a Special Case — If nitrides may be considered to be intermetallic compounds then the nitrified steels furnish excellent examples of the formation of such compounds. The aluminum-bearing steels especially, and other compositions to some degree at least, present an interesting example of the formation of a dispersion of hard particles of great fineness. Perhaps, as in other effective hardening dispersions, the so-called "particles" are, when at the most effective size, not large enough to be regarded as crystallites at all but are rather only the simplest molecules. It is reasonable to suppose that at the customary nitriding temperature, 1100 degrees Fahr. (600 degrees Cent.), nitrogen combines with each aluminum atom dispersed in the ferrite but that there is substantially no diffusion of aluminum at this temperature and that therefore the molecules (or "knots") of hardening agents remain at the magnitude of maximum hardening effect. If this is correct then in nitriding a dispersion of optimum characteristics (i.e., no crystallites) is actually created *in situ* by the diffusion of the nitrogen. Any diffusion of the metal in the nitride would remove one of the local disturbing knots for each doubling of any molecule, — an over-all softening effect. The exceedingly

high hardness of the nitrified layer requires for its explanation a mechanism of extraordinary effectiveness and one which does not postulate, or allow, the dark-etching effects generally found in ordinary precipitation-hardened alloys, but not observed in nitrified steels. No doubt the mechanism of nitride hardening is somewhat the same for aluminum alloys and for the alloy steels described as being substituted therefor. There are probably other compounds which could be formed from one element of high diffusivity and the other of great immobility which would likewise result in the maximum hardening possible for dispersed systems.

EFFECTS OF ELEMENTS IN DISPERSED METALLIC PARTICLES

In addition to carbides, nonmetallic and intermetallic particles, it is possible for added elements not dissolved in ferrite to appear in yet another form. If no compounds are formed the excess beyond the solubility in ferrite may appear as particles of the element itself. These particles will, of necessity, be saturated with respect to iron.

Thus copper, which is soluble in large proportion in gamma iron is, at the maximum, dissolvable up to only about 3 per cent in ferrite at 810 degrees Cent. At 1100 degrees Fahr. (600 degrees Cent.) the solubility is probably not much in excess of 0.5 per cent. The copper dissolved at elevated temperature is rejected as nearly pure copper particles. Alloys of some 1.5 to 1.75 per cent copper, accordingly show definite age-hardening characteristics.

Probably lead beyond a mere trace is present in iron alloys as particles of metallic lead. The particles, however, if formed in alloys of about 0.25 per cent lead are reported as being difficult to observe microscopically, owing presumably to some circumstance of their mode of rejection or their fineness.

SUMMARY OF ALLOYING ELEMENTS IN UNHARDENED STEELS

In this third chapter of these discussions of alloying elements the alloy steels have been considered in their ferrite-plus-carbide state wherein the carbide phase has had opportunity, through comparatively slow cooling, to form particles or platelets of such considerable magnitude as not to constitute the dominant and overpowering factor in the strength of the steels. This structure indicates an approach to equilibrium sufficient to permit the composition of the phases to approximate that at the state of equilibrium wherein the alloying elements locate themselves according to combining tendencies rather than according to diffusion limitations.

Partition of Elements Between Ferrite and Carbide—

It has been brought out that nickel, silicon, aluminum and much of the manganese in the steel is dissolved in the ferrite regardless of the carbon content, but that the titanium, vanadium and columbium are combined, as far as the excess carbon content permits, in the carbide phase. Several elements occupy an intermediate position. Chromium is somewhat dissolved in ferrite even with high carbon, while only a moderate portion of the tungsten, molybdenum and tantalum are to be found in ferrite under similar conditions. The elements which combine with oxygen, and are therefore eliminated by flotation or occasionally exist in nonmetallic inclusions, are identified as aluminum, zirconium, beryllium, silicon, vanadium, etc. The possibility of intermetallic compounds was discussed as well as the special hardening influence of nitrides in superfine dispersion built *in situ*. The role of manganese sulphide in aiding machinability is important. Primarily, however, the capacity to form special carbides was stressed.

Steels Dominated by Alloy-Bearing Ferrite — The real interest in this matter of the distribution of the elements in annealed, or approximately equilibrated, steel is in connection with the properties of alloy-bearing ferrite which is obviously

the primary consideration of alloying elements in very low-carbon steel, and a dominant one in thoroughly annealed steel of medium carbon content. The effect exerted through strengthening ferrite is found to be relatively small taken alone, and this circumstance is no doubt responsible for the old, but inaccurate, generalization that alloying elements are effective only in heat-treated steels. The effect, small though it appears, generally connotes a gain of strength at the cost of a very small loss in ductility and plasticity.

Low-Alloy, High-Strength, Structural Steel — Indeed, the benefit of alloying elements in unhardened steel is the major factor in certain high-strength structural steels to which welding operations are to be applied without any special auxiliary precautions. The metallurgical significance of these requirements is that the steel must be stronger than carbon steel as slowly cooled, but still not deficient in ductility after the rapid cooling inherent in fusion welding. Steels of this class must be sufficiently low in carbon, manganese and all so-called deep-hardening elements as to insure that the hard products of austenite transformation are not formed upon rapid cooling because of their lower ductility. Such microstructures as have been designated as troostite (i.e., fine pearlite) or particularly martensite, if they carry medium carbon, lack adequate ductility. Accordingly the superior strength which otherwise might, in the rolled condition, have been derived from carbon, must be provided by dissolved alloying elements acting largely by solid-solution effect.

In these high-strength, low-alloy, structural steels, chromium, nickel, silicon, phosphorus, copper, manganese and molybdenum are variously employed with a carbon content limited to 0.10 to 0.15 per cent, depending upon the hardenability contributed by the alloys. The steels permit considerable saving of weight, particularly in members bearing tensional load, and in moving structures this saving of

weight affords great economies. In many structures in which the extra strength permits a reduction of section, corrosion is to be reckoned with for the thinner sections would be relatively more seriously weakened by any certain degree of corrosion than the thicker sections of ordinary carbon steel. Accordingly it is very advantageous to develop a proven resistance to corrosion in this class of steel compositions. The rate of corrosive attack in a number of environments is reduced several fold by the presence, for example, of chromium, copper and upwards of 0.10 per cent phosphorus. It is customary to design this family of steels for a yield point of about 50,000 pounds per square inch. Compositions with much higher yield point generally possess a degree of hardenability which may interfere, in some applications, with adequate ductility following the rapid cooling in the vicinity of ordinary welds. When annealing treatments may be applied after welding or even other special welding procedures, such as preheating, are resorted to, steels of still higher strength are well suited to welded structures. The class of high-tensile structural steels is of interest at this point because they represent a very valuable utilization of alloying elements in unhardened steel wherein the solid-solution effect of elements upon ferrite is the main source of added strength accompanied by good ductility.

Special Low-Carbon, High-Alloy Steels — As already mentioned in the introduction, time does not permit of any extended consideration of the steels which are characterized by some special property, such as corrosion resistance, which is secured by a large proportion of alloying elements. Briefly, it appears that a presentation of a minimum ratio of about 1 atom of chromium to 7 atoms of iron at a surface makes possible the acquisition of an impervious film, presumably of oxygen, which then blocks further reaction of the metal with an oxidizing environment. Certain combinations of elements,

in much smaller proportions, such as phosphorus, copper and chromium act to restrain rusting, even though they do not initially prevent it. In this instance, it appears, the product of corrosion, instead of being porous and hygroscopic, is more nearly integral and, after initial corrosion, greatly retards further inroad especially in the form of local intense action or pitting. The high-chromium, corrosion-resisting steels, classed as stainless steel, usually carry low carbon for several reasons, — one being the saving of chromium which would otherwise be wasted as carbide in the annealed condition. The chromium ferrites are soft even when they contain a high chromium content.

Time does not permit the discussion of another interesting low-carbon alloy steel, the silicon magnetic material. Silicon here acts to increase electrical resistivity and to facilitate the formation of well-crystallized ferrite grains.

Other ferrous alloys which, however, are not usually classed as steels are the iron-tungsten, iron-molybdenum and iron-titanium age-hardening alloys with or without cobalt.

Typical Property Changes Induced by Alloying Elements

— It is helpful to bear in mind the broad effects of carbide distribution which are similar for the cementite of carbon steel and for the alloy-bearing and special carbides; as developed in the first chapter they may be reviewed here. These principles relating to the effect of amount, form and fineness of the carbide dispersion, explain most of the properties of unhardened alloy steel if one will superpose these effects upon a basis recognizing the modified matrix of ferrite. By and large the same factors operate in the same way.

- A. The coarser the carbide particles the less is the influence upon strength.
- B. The lamellar dispersions, within the limits of fineness encountered, contribute strength with lower resulting plasticity than do the spheroidal carbide particles producing equal hardness.

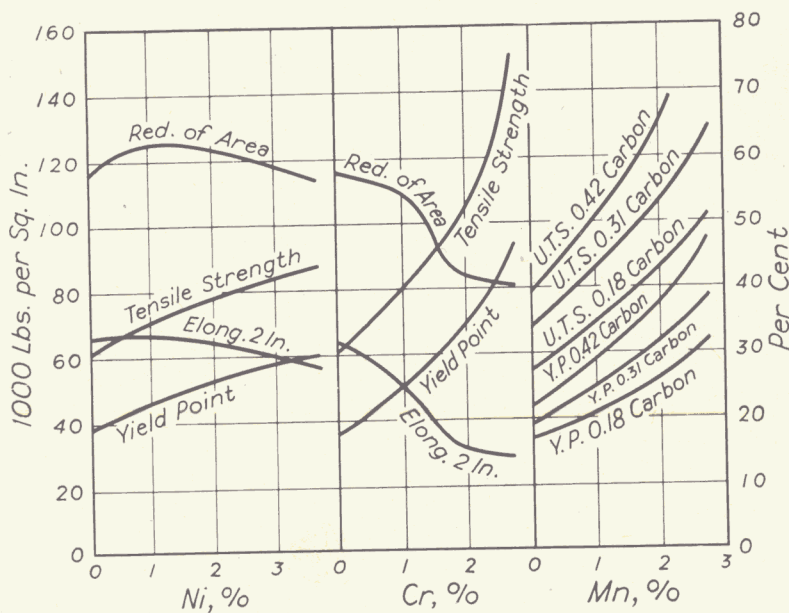


Fig. 52—Effect of Nickel Content upon the Tensile Properties of 0.20 Per Cent Carbon Steels as Rolled. (Courtesy H. J. French, International Nickel Company).

Fig. 53—Effect of Chromium Content upon the Tensile Properties of 0.20 Per Cent Carbon Steels as Rolled. (Courtesy A. B. Kinzel, Union Carbide and Carbon Company).

Fig. 54—Effect of Manganese Content upon the Strength of Low and Medium Carbon Steels as Rolled.

- C. Intergranular carbide envelopes greatly embrittle the steel.
- D. The alloy-bearing carbides, either of the cementite or special crystal type, have, in corresponding dispersions, essentially the same influence upon ordinary room-temperature tensile and impact properties as have cementite dispersions, but may exert special effects upon such special properties as abrasion resistance.

Except when special precautions are taken in an experimental way to insure equivalent microstructures in carbon and different alloy steels, the structures themselves in the regular air-cooled steels will be influenced by the alloying elements; always toward a finer, stronger structure. In low-

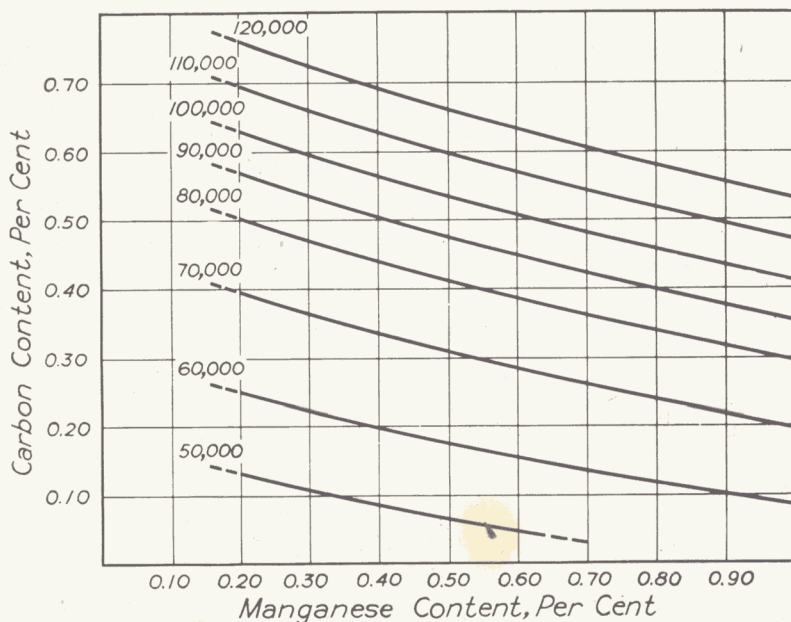


Fig. 55—Approximate Compositions (Carbon and Manganese) as Required to Produce Various Tensile Strengths as Indicated in As-Rolled Steel. (Compiled from work of Webster²).

carbon compositions this influence is small at low alloy content but gradually increases. Thus Fig. 52 shows the effect of nickel content upon the tensile properties of 0.20 per cent carbon steels as air-cooled from rolling to a $\frac{1}{2}$ to $\frac{3}{4}$ -inch section. Note that the ductility is actually thought to be increased by small additions of nickel.

Fig. 53 shows the effect of chromium upon the tensile properties of 0.20 per cent carbon steels in the same as-rolled conditions as for the nickel steels of Fig. 52. Note the departure from the simple solid-solution effects at about $1\frac{1}{2}$ per cent chromium. The strengthening effect at low chromium is only a little more potent than for nickel, but influences more effective than solid-solution in ferrite soon manifest themselves in higher proportions.

Manganese increases strength at nearly the same rate as chromium, and beyond a content of some 2 per cent even in very low carbon steels exerts a powerful influence toward micro-structural changes, which detract from ductility. Fig. 54 shows approximately the effects of manganese upon 0.20, 0.30 and 0.40 per cent carbon steels with respect to yield point and ultimate strength. A review of the comprehensive work of Webster⁹ indicates that the combined effects of carbon and manganese in unalloyed open hearth steels as rolled are about as shown in Fig. 55, which, by smoothed curves, presents the combinations resulting in certain definite tensile strengths. The figure indicates that factors other than mere solid-solution hardening are exerting a dominant influence.

This alloy influence, which is obviously one of creating harder and stronger *structures* at the same cooling rate, is by all odds the most important one exerted by the elements and forms the subject matter of the following chapter.

Individuality of the Elements in Unhardened Steel—

It has perhaps been helpful from time to time to point out the various broad similarities among the several alloying elements in unhardened steel, particularly with reference to the contributions of hardness and strength as measured by the tensile test. It has already become apparent, however, that, in degree of influence, they vary markedly; and that they are not exactly similar in respect to the loss of plasticity accompanying a gain in strength. The highly individual characteristics of the elements with respect to their effects upon the special mechanical properties when partly dissolved in ferrite and partly incorporated in carbide is well worth study. These inherent variations are well illustrated in a comparison of three 0.35 per cent carbon steels:

A. Straight Carbon Steel, 0.35 per cent carbon.

B. 2.0 per cent Chromium Steel, 0.35 per cent carbon.

⁹"Application in Rolling of Effects of Carbon, Phosphorus and Manganese on Mechanical Properties of Steels", by W. R. Webster, *Transactions*, American Institute of Mining and Metallurgical Engineers, Vol. 67, 1922, p. 220-256.

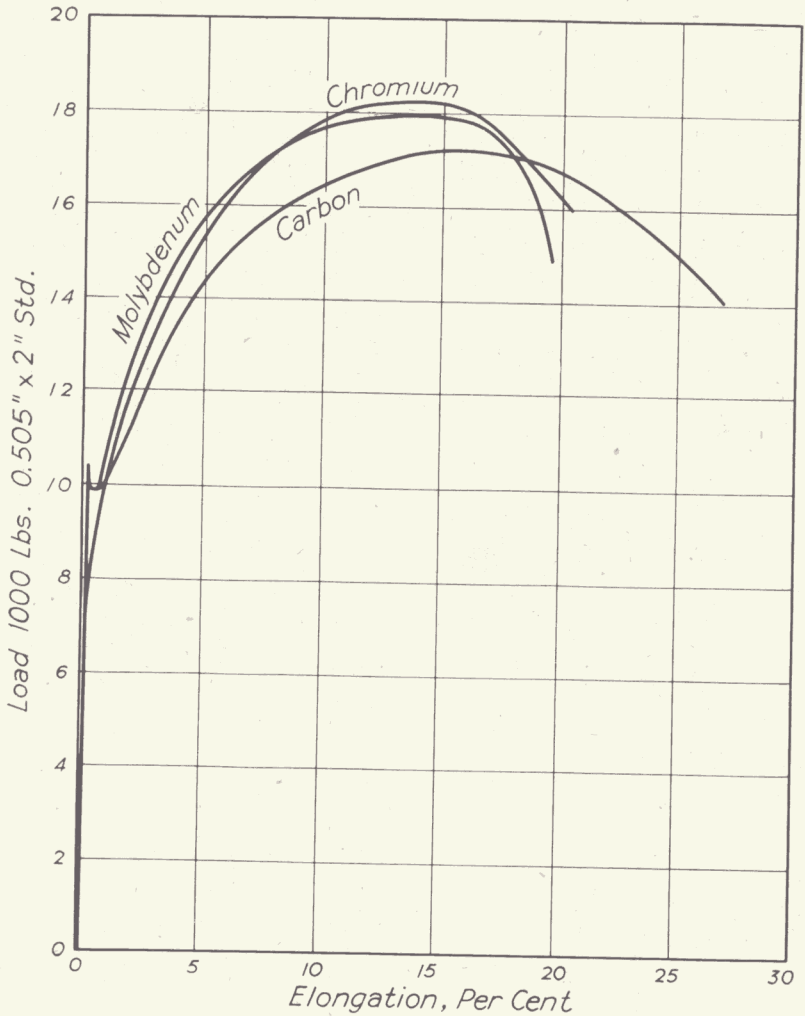


Fig. 56—Stress-Strain Diagrams for Three 0.35 Per Cent Carbon Steels: A—Straight Carbon; B—2 Per Cent Chromium; and C—2 Per Cent Molybdenum. Standard 0.505 Test Specimens. (See Footnote 10).

C. 2.0 per cent Molybdenum Steel, 0.35 per cent carbon. The steels are investigated¹⁰ at the same hardness, 180 Brinell.

¹⁰The painstaking preparation and testing of the specimens of these three compositions were carried out by R. F. Miller, R. F. Campbell, W. G. Benz, W. E. Unverzagt, W. B. Seens and W. H. Sparrow of the United States Steel Corporation Research Laboratory.

To secure the same hardness for all, bars of each were cooled from a temperature well within the austenite range, each at its own appropriate rate. The structure of the bars as tested was that acquired by transformation upon slow cooling; i.e., ferrite and pearlite, and some spheroidization since the molybdenum steel was of necessity cooled at a relatively slower rate to insure the low hardness. At similar hardness, standard tensile tests produced the load-deformation (so-called stress-strain) diagrams of Fig. 56. The data follow:

	A Carbon Steel	B Chromium Steel	C Molybdenum Steel
Ultimate Ten. Str.	86,300 psi	91,300 psi	89,600 psi
Yield Point	50,200 psi	52,100 psi
0.01 per cent Set	50,200 psi	28,000 psi	51,500 psi
0.1 per cent Set	49,100 psi	37,000 psi	49,700 psi
0.2 per cent Set	49,300 psi	39,500 psi	49,700 psi
Elongation 2 Inch	27.0%	20.5%	19.7%
Elongation 2 Inch (Unif.)	16.6%	13.7%	14.0%
Reduction of Area	55.0%	44.2%	44.3%
Stress at Rupture	155,000 psi	142,000 psi	133,000 psi

Here a uniform hardness is accompanied, as would be expected, by little variation in tensile strength but the elements have not contributed anything to plasticity. The chromium steel shows no yield point elongation and has a relatively low proportional limit. The alloy effects are thus individually distinct.

Consider now the notch toughness of the three steels as measured at substantially identical hardness in the Charpy Test:

	A Carbon Steel	B Chromium Steel	C Molybdenum Steel
Charpy Impact (Ft.Lbs.)	25	8	11

Here the notch toughness is seen to differ among the steels in a manner quite distinct from that of plasticity in the

tensile test. Indeed since the Charpy Test purports to measure, in effect, the ability of metal to flow under most adverse conditions of disruptive load in reference to the shearing load there is no reason to expect a parallel. Note again that the alloying elements *in this condition* have not contributed a valuable property.

Consider now the ability of the metal to sustain prolonged deformation under more favorable conditions of load-

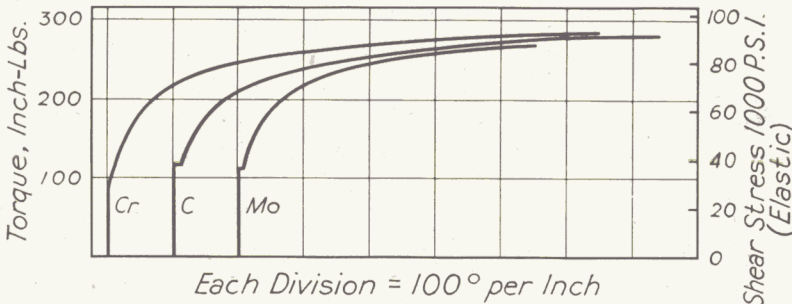


Fig. 57—Torque-Angle of Twist Curves for Steels of Fig. 56 as Secured by the Torsion Test on ¼-Inch Diameter Specimens. (See Footnote 10).

ing (wherein the maximum disruptive force is only equal to the shearing force). Such a condition is set up in the torsion test, the results of which are shown graphically in Fig. 57. Somewhat analogous to the familiar stress-strain diagram of the tensile test, these graphs show the angular deformation or twist as a function of the applied torque. Over the purely elastic range the maximum shear-stress (developed at the surface) may be computed and this derived figure is shown as a supplementary scale. The essential data are as follows:

	A Carbon Steel	B Chromium Steel	C Molybdenum Steel
Twist per Inch (Degrees)	740	748	454
Torque at Yield	120 In.Lbs.	No Y. P.	114 In.Lbs.
Torque (Maximum)	278 In.Lbs.	281 In.Lbs.	264 In.Lbs.
Shear Stress at Yield	38,700 psi	37,400 psi

By this mode of study all the three steels exhibit great plasticity, but in degrees which are characteristic of the individual elements. It will be seen that an early lapse into plastic deformation does not indicate the greatest ability to endure continued deformation. Again the order of the effects is not the same for the two elements as in other tests.

Apart from establishing the individual characteristics of the alloying elements with respect to subtle fundamental properties conferred when the steels are at about the same hardness, another purpose is served by this demonstration. At first glance it might seem that a poor case, rather than a good one, had been made for the use of alloying elements. On the contrary, it indicates that, by design, structures can be developed which almost preclude taking advantage of the usefulness of the alloy influences;—indeed may almost turn these good influences to disadvantage. Had even these particular bars been tested for creep at elevated temperature, for instance, there would have been still another story to tell.

The comparison of the three steels, slowly cooled to develop low hardness by direct transformation, will have served a good purpose if it merely places the proper emphasis upon the necessity of adjusting the heat-treatment to suit the composition. The impression that the alloying elements may be indiscriminately employed to enhance all properties under all conditions, if such exists, may be more easily dispelled by reviewing these tensile, notch impact and torsion tests. To entertain such a view is to risk losing the potential dividends which may accrue from the investment involved in the cost of the alloys.

The following chapter is devoted to the behavior of the alloying elements in heating of the steel to heat-treating temperature,—the first operation in developing the structure which fosters the realization of the enhanced properties of alloy steel.