

July 3, 1951

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2,559,016

METHOD FOR DETERMINING HARDENABILITY OF STEEL

Original Filed June 25, 1942

3 Sheets-Sheet 1

FIG. 1.

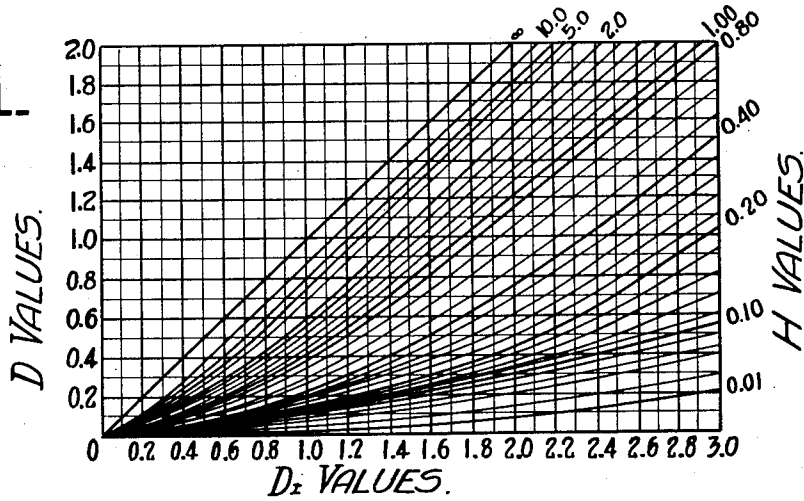


FIG. 3.

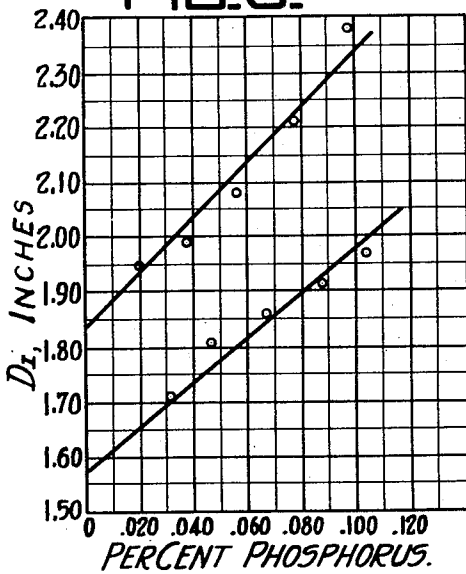
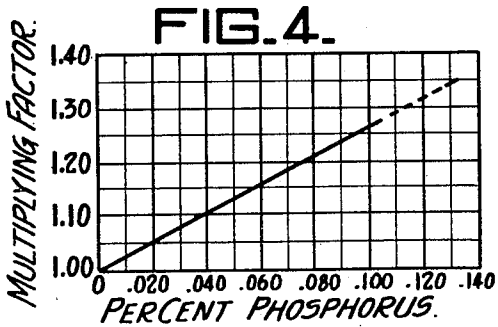
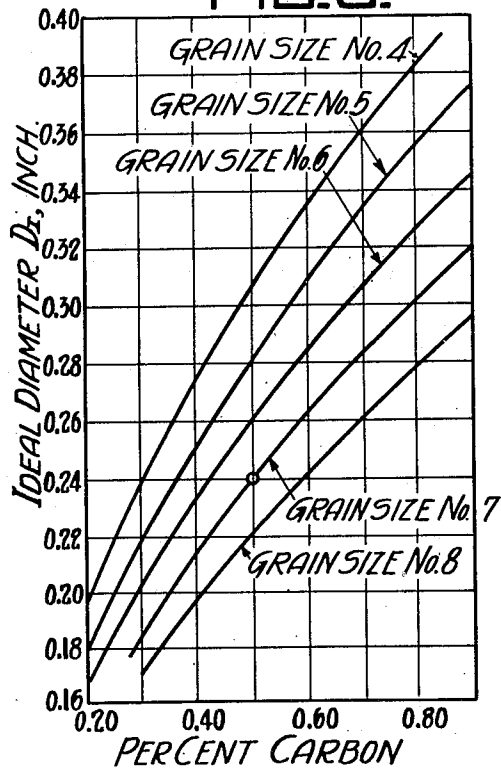


FIG. 5.



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FIG. 2.

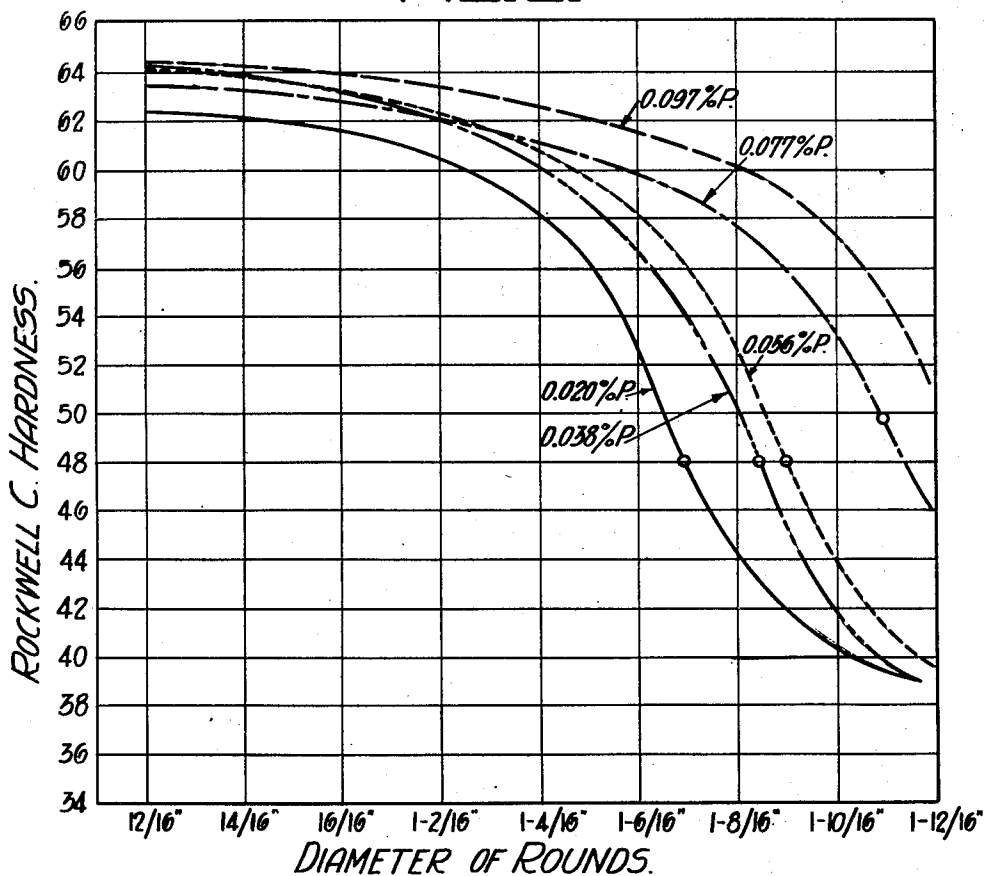
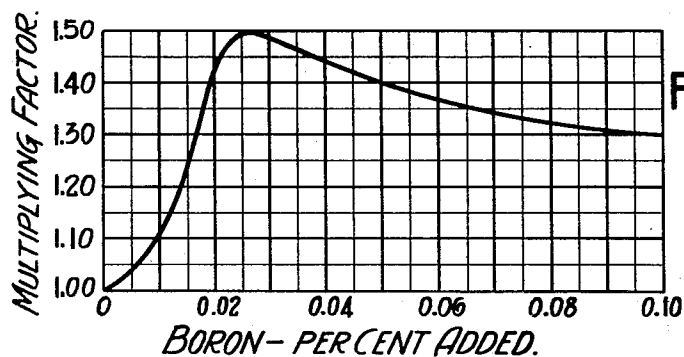


FIG. 8.

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FIG. 7.

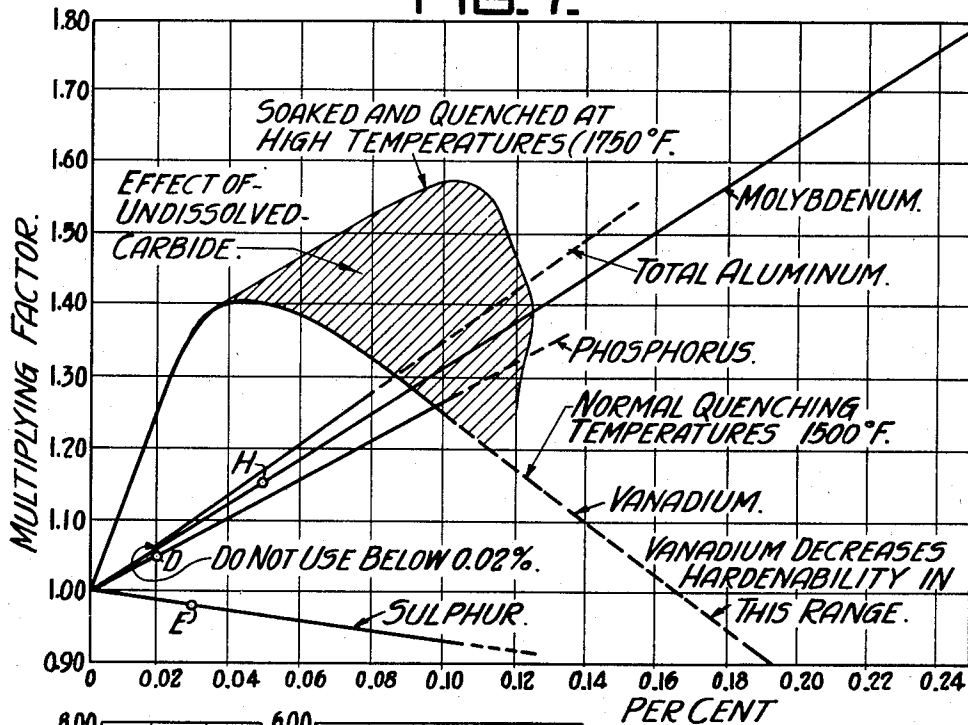
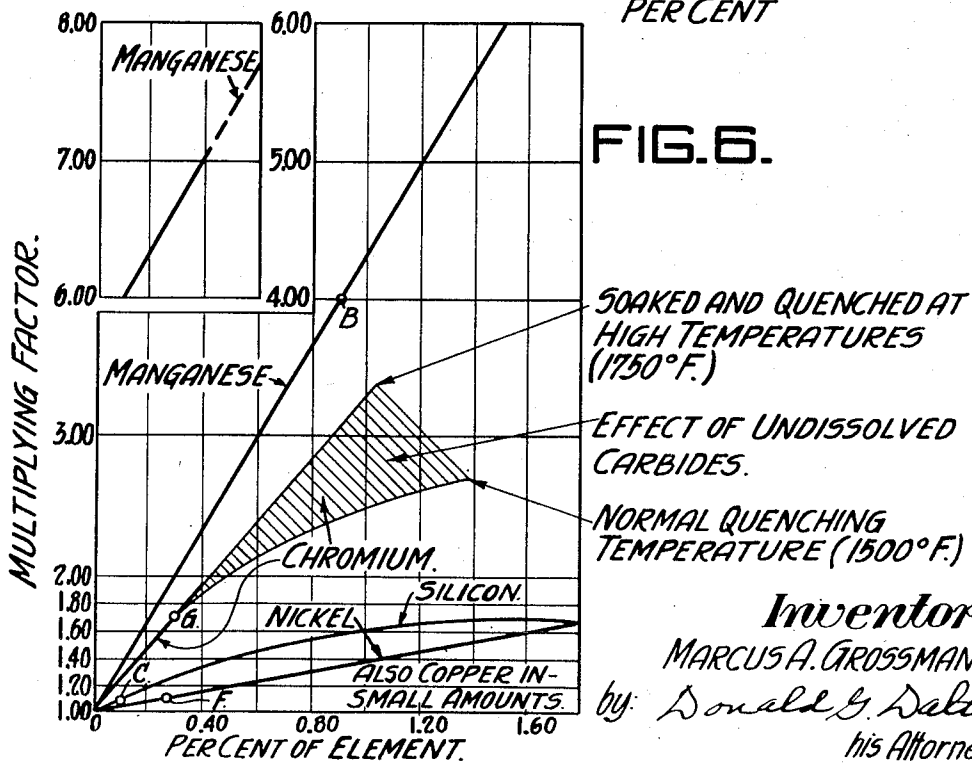


FIG. 6.



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UNITED STATES PATENT OFFICE

2,559,016

METHOD FOR DETERMINING
HARDENABILITY OF STEELMarcus A. Grossmann, Pittsburgh, Pa., assignor
to United States Steel Company, a corporation
of New JerseyOriginal application June 25, 1942, Serial No.
448,453. Divided and this application May 31,
1945, Serial No. 596,921

1 Claim. (Cl. 73-15)

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This invention relates to a method of determining in advance the hardenability of an alloy steel of a given composition or, conversely, of determining what alloy elements and how much of each will be necessary to produce a steel having a desired hardenability.

It is well known that identical quenching treatments cause heavy sections of different alloy steels to harden to various depths. Measuring hardness values from the surface to the center of corresponding specimens shows that the location of points of a given hardness may vary within a relatively wide range of distance from the surface. The depth from the surface at which a given hardness can be recorded after quenching is known as "hardness penetration," and the property of steel which determines the hardness penetration after standard quenching treatment is called "hardenability."

Theoretical considerations fully supported by extensive practical experience show that hardenability has a far reaching effect on industrial value of steels, constitutes an index to the various physical properties of the metal including its yield point, elongation, hardness, hardness penetration and other characteristics of immediate interest to steel users.

It has been recognized for a long time that hardenability is a function of several factors, including among them the grain size and alloying constituents of steel. A large amount of work has been done in attempts to determine the exact effect of these factors on the response of steel to hardening, and to develop suitable generalizations for predicting the hardenability of a given steel without actually making the steel and subjecting specimens to hardening. Certain of these generalizations, expressed in formulas relating hardenability to grain size and composition, permitted evaluation of this property of steel in advance of manufacture and test, with reasonable accuracy, but only within a limited range of factors. Investigators failed to discover any universally applicable generalization for the relation between different factors and hardenability or to suggest a formula, or propose a law, embracing this relation within the whole field of industrial applications. No method has been known for determining this relation, and no method was available for determining hardenability of a steel in advance of actual quenching of specimens thereof.

An object of the present invention is a method for determining the relation between grain size, composition, and hardenability of steel.

A related object of the present invention is a method for predetermining hardenability of steel from its composition and grain size.

The desired relation between composition and grain size of steel and its hardenability is deter-

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mined, according to the present invention, by evaluating the individual effect of each component of steel, including so-called residual elements, on hardness penetration, totalling such effects, and adjusting this total effect on hardenability in the light of grain size of the steel.

In carrying out the invention, the individual effect of elements composing steel on hardenability is evaluated by alloying with molten steel different amounts of the elements under consideration and determining their influence on hardenability characteristics. In the preferred method of this invention, the required amounts of a desired alloying element are added to the metal of the same heat while being teemed into successive ingot molds. This practice is followed in order to assure the identity of the base used for the whole series of additions. It has been found that the composition of the base metal has substantially no influence on the results obtained, provided it does not vary within any one series.

Alloy ingots cast in the above manner are allowed to solidify and then subjected to conventional manufacturing steps for bringing them to the final dimensions suitable for specimens to be used in actual hardening processes. Specimens are preferably homogenized by an appropriate preliminary heat treatment and machined to meet the requirements of surface and dimensions imposed by the specifications of the hardening test. After being heated to the desired critical temperature under conditions reducing oxidation of the surface, specimens are quenched in a bath under constant conditions.

Quenched specimens, commonly round bars, are sectioned and the extent of hardness penetration determined. Since the boundary line between hardened rim and unhardened core has been used for many years for judging the depth of hardening and since the composition of the steel at this boundary line corresponds to 50 per cent martensite, the 50 per cent martensite concentration is used in the present method as the criterion of hardness penetration and the criterion of hardenability adopted in the present method is the distance from the surface of specimen at which the steel contains 50 per cent martensite.

It is, however, more advantageous, from the standpoint of experimental convenience, to express hardenability in terms of ideal critical diameter, which is the diameter of the bar in which the hardened rim extends just to the center, or in which the unhardened core is just absent after the bars have been cooled instantaneously to room temperature. This criterion has a special advantage in practical hardenability determination, since the diameter at which the unhardened core is small is very sensitive to changes in hardenability. The ideal critical diameter D_i is a true measure of hardenability alone, since

it refers to a constant severity of quench, it can be accurately determined, is applicable both to high and low hardenability, is related to already familiar manner of testing by depth of hardening, and can be readily visualized for practical applications being the size which will just harden throughout in the severest possible quench.

Actual hardness measurements have been found inadequate for determining hardenability within the meaning of the present invention. Hardenability depends by its definition on the location of the 50 per cent martensite boundary line. Experience has demonstrated that even at the 50 per cent martensite boundary there are wide variations of actual hardness. This hardness ranges in plain carbon steels from substantially 32 Rockwell C for a 0.20% C steel to about 55 Rockwell C for a 0.90% C steel, showing even greater variations when alloying elements are present in the metal.

A combination of hardness measurements with certain additional steps, however, offers fully adequate means for hardenability determination. Properly quenched specimens are sectioned transversely to their long axes, and hardness determinations are made at small intervals from the surface to the center. A hardness-testing device similar to Rockwell C hardness tester has been found satisfactory for the purpose, and one-sixteenth-inch intervals provide a sufficient closeness of measurements without unduly complicating testing operations. Hardness figures are recorded and plotted against the distance from the surface. An inflection in the curves so produced indicates the area, when present, of a 50 per cent martensite alloy. Its presence can be then verified under a microscope, or by fracturing.

A further simplification of the above method is possible and has been widely used in the development of the present invention. A series of round bars having progressively increasing diameters is prepared from the experimental steel. These diameters are selected to provide a minimum diameter sufficiently small to assure hardening throughout, and a maximum diameter adequate to provide an unhardened core. Center hardness is determined on each of these bars after quenching and is plotted against the diameter. The point of inflection of these curves read as a function of diameter gives directly the critical diameter for the quenching conditions used.

Critical diameters obtained in the manner described fail to account for the rate of heat absorption from the samples by the quenching medium, commonly referred to as "severity of quench," which is a function of the nature of quenching medium and of the method of its application. Two bars of steel entirely alike in every respect and subjected to quenches of a different severity will result in a different depth of hardening or a different critical diameter. No reliable comparison of critical diameters of tested bars is, therefore, possible unless the severity of the quench actually employed is reduced to some standard value.

The conception of ideal critical diameter underlying the present invention expresses hardenability in terms of the hardenability obtained in the ideal (severest possible) quench. The invention furthermore provides charts similar to that shown in Figure 1 for direct conversion of critical diameter obtained by actual quenching to corresponding ideal critical diameter as a func-

tion of severity of actual quench. In these charts, the ordinates are the values of critical diameter designated D , the abscissae are values of the ideal critical diameter D_i , and the several curves show the relation therebetween for various values of the severity of quench H . The theory and derivation of these charts have been elaborately described by the inventor in the magazine *Iron Age* of April 25, 1940, pages 25 to 29, and of May 2, 1940, pages 39 to 45.

Critical diameters determined by quenching appropriate samples are converted to ideal critical diameters by the use of the chart given in Figure 1, or its equivalents, and are plotted using concentration of element under investigation as abscissae and ideal critical diameter as ordinates. The curve obtained by this method relates hardenability directly to the concentration of the element in question.

The ideal diameter D_i denotes, as mentioned previously, the size of bar that just hardens fully, without an unhardened core, in an ideal (severest possible) quench. Actual quenches in practice are less drastic than the ideal quench, so that the size which will just harden fully is smaller than the ideal diameter D_i . The size that just hardens in any actual quench may be predicted by the use of Fig. 1. In order to be able to use Fig. 1, it is necessary to know the severity of the quench. If it is not feasible to ascertain the severity of the quench experimentally, the figures in the following table may be used as a guide:

Severity of quench

	Oil	Water	Brine
No circulation of liquid or agitation of piece.....	0.25 to 0.30	0.9 to 1.0	2
Mild circulation (or agitation).....	0.30 to 0.35	1.0 to 1.1	2 to 2.2
Moderate circulation.....	0.35 to 0.40	1.2 to 1.3	-----
Good circulation.....	0.4 to 0.5	1.4 to 1.5	-----
Strong circulation.....	0.5 to 0.8	1.6 to 2	-----
Violent circulation.....	0.8 to 1.1	4	5

In the graph shown in Figure 1, the numerical values of D and the numerical values of D_i represent units of length, the units of length being the same for each. Thus, such values may represent inches in one case, millimeters in another, and centimeters in still another instance. The top line in such graph, which is a straight line running from the zero point to the value of 2.0 for both the D and the D_i values, represents the ideal quench, that is, the instantaneous reduction of the temperature of the specimen to 70° F. which, of course, is impossible of attainment. The other curves in such graph represent quenches of varying degrees of severity, such quenches being evaluated numerically in accordance with the table above.

An experimental determination of the influence of phosphorus on the hardenability of steel is given herebelow as a numerical illustration of the principles involved in the part of the present invention relates to the determination of the effect of individual elements on the hardenability of steel.

A series of steels having selected increments of phosphorus content was made by adding calculated amounts of powdered 24 per cent ferro-phosphorus to the bottom two-thirds of four successive ingots of a heat containing 0.59% C, 0.93% Mn, 0.018% P, 0.18% S, 0.22% Si. These ingots were rolled to 3 3/8" square billets, and the two middle billets of each test ingot and of an ingot to which no ferro-phosphorus had been added

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were used for testing. Chemical analysis showed these ingots to have the following composition:

Ingot No.	C	Mn	P
16 (untreated)	0.62	0.98	0.020
17	0.62	1.00	0.038
18	0.61	0.98	0.056
19	0.62	0.98	0.077
20	0.61	0.98	0.097

Quarter-sections 6" long were cut from these billets, heated for two hours at 1500° F. and cooled in still air to effect their normalization. These quarter sections from each ingot were turned into rounds ranging from ¾" to 1¾" diameter, heated at 1500° F. for two and one-half hours, and quenched vertically in water to 75-90° F. The quenched bars were sectioned perpendicularly to their long axis, and the hardness gradient from edge to center was determined for each round by taking Rockwell C readings at ¼" intervals on two mutually perpendicular diameters.

The hardness values recorded in this manner were plotted against the distance from the surface. Then hardness at the center of each bar was plotted against its diameter. The resulting curves are shown in Figure 2 of the drawings, using circles to indicate the estimated position of the inflection points of the several curves. The relative position of the inflection point shifts to the right with the increasing phosphorus content. For the lowest phosphorus content of 0.020%, it corresponds to a critical diameter of 1⅞ inches, and for steel containing 0.077% phosphorus, the figure obtain is 1⅞ inches. The range of sizes employed was not sufficient to include the critical section of the ingot containing 0.097% phosphorus. The indications furnished by inflection points on these curves were then checked under the microscope and by fracture observations. It was found that the points of inflection substantially coincided with the presence of 50 per cent martensite in corresponding samples, and to hardness penetration just to the center of bars having corresponding diameters. These observations were further supported by conducting a similar series of experiments on steels having a greater hardenability and containing 0.63% carbon, 0.94% manganese, 0.027% sulphur, 0.027% silicon, 0.02% copper and varying percentages of phosphorus.

The critical diameters obtained by the above experiments were converted to ideal critical diameters by means of the diagram of Figure 1 and plotted against phosphorus content, as shown in Figure 3. Two straight lines, one for each steel, are drawn to represent the increase in hardenability due to phosphorus. The slopes of these lines indicate the same increase of hardenability being caused by identical phosphorus percentage in the high hardenability and low hardenability steel, while the individual disgressions from the straight line are less than 2.5 per cent in terms of the ideal critical diameter. When the line given in Figure 3 is extrapolated at 0.0% phosphorus, it shows a value of ideal critical diameter equal to 1.574 while the same steel at 0.100% phosphorus has an ideal critical diameter of 1.980. This increase from 1.574 to 1.980 is an increase of 26 per cent in the value of ideal critical diameter for a phosphorus addition of 0.100%. Since the ideal critical diameter increases as a straight line function of the phosphorus content, and this increase amounts to 26 per cent on adding 0.100% phosphorus, the

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effect of phosphorus on hardenability can be expressed by the diagram given in Figure 4.

A comprehensive series of experiments, conducted in a manner described in connection with the determination of the hardening effect of phosphorus, was conducted using properly selected steels containing progressively increasing percentages of carbon, manganese, silicon, copper, sulphur, chromium, nickel, vanadium, molybdenum, aluminum, and boron. It has been found that the relation between the percentage of additional elements and the corresponding ideal critical diameter within the ranges investigated, basically followed a straight-line law. Since the whole concentration range has not been investigated, and since secondary reactions enter the effect of certain alloying elements, the diagrams obtained in the course of these experiments expressing the influence of different elements or hardenability given in Figures 5 through 8 occasionally deviate from the straight-line function. They show graphically, however, the effect of alloying-elements concentration on the ideal critical diameter. Figure 5 shows the effect of carbon and grain size on the hardenability of steel. Figure 6 illustrates the influence on hardenability of manganese, chromium, silicon, nickel and copper. Figure 7 shows the effect on hardenability of molybdenum, aluminum, phosphorus, sulphur and vanadium. Figure 8 demonstrates the effect of boron on hardenability.

It has been suspected that steel composition and the grain size of austenite about to be quenched are two major controlling factors in the hardenability of steel. Since the effects of grain size and composition are present simultaneously in any observed hardenability behavior, it becomes necessary to distinguish between the two effects. According to the present invention, the separation of the effect of grain size and determination of the numerical values of the latter have been done following substantially the practice described in connection with the determination of the influence of phosphorus, modified in the light of specific requirements of the subject.

Steels selected for determining the effect of grain size contained:

Steel	Carbon	Manganese	Silicon
A	0.43	0.71	0.19
B	0.55	0.76	0.18
C	0.79	0.62	0.21
D	0.35	1.68	0.22

These steels were rolled and machined into samples in the manner described for the determination of the effect of phosphorus on hardenability. After normalizing, cylindrical samples were heated at 1430° to 2100° F. and held at the temperature for five hours to impart different sizes to the austenitic grain composing them. The heated bars were directly transferred from the high-temperature furnace to a salt bath held just above the upper critical temperature. The bars were held in the salt bath for a time sufficient to lower their original temperature to that of the bath, thus keeping them in a wholly austenitic state while retaining the grain size corresponding to the original high temperatures. The bars were then quenched and their hardenability characteristics obtained both as a function of grain size, and of carbon content. These data are shown in Figure 5 in which ideal critical

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diameter is plotted against the carbon content of steel as a function of grain size.

The manganese and silicon contents in each of steels A, B, and C above are well within the limits which are considered identical in production practice. The data obtained from following the above procedure on steels A, B, and C were employed in making the curves appearing in Figure 5. The data obtained from similar procedures conducted on steel D, which differs markedly from the other three steels in manganese content, were employed only as a check upon the results shown in Figure 5.

A major contribution of the present invention to the art is the discovery that the total hardening effect of all the alloying elements is the product of the effects of the individual elements. In all formulas proposed hitherto for predetermining hardenability characteristics of steel, the effects of the different elements were considered to be additive. A quantity was assigned to each element, and the sum total of them represented the value sought. The method of the present invention is based on the discovery that a steel composed only of iron and carbon, in which no other element is present, has a certain hardenability, and that each additional alloying element is represented by a factor by which the original hardenability is multiplied. Thus the final hardenability of any steel is the product of the original hardenability of a corresponding iron-carbon alloy multiplied by factors for all the alloying elements present in the steel corrected for its grain size.

As a numerical illustrative example of the teachings of the present invention I explain below the practice followed in determining hardenability of a steel having a grain size of 7 and containing 0.50% carbon, 0.90% manganese, 0.10% silicon, 0.020% phosphorus, 0.029% sulphur, 0.28% nickel, 0.30% chromium, 0.05% molybdenum and 0.05% copper.

The basic hardenability for this steel is derived from the curves of Figure 5, where point A corresponds to 0.50% carbon and No. 7 grain size. This point corresponds to an ideal critical diameter of 0.24, which is the diameter of a bar which will harden at the center of 50 per cent martensite when its surface is instantaneously cooled to 70° F. This base hardenability is multiplied by a factor specified by 0.90% manganese present in steel, namely by a factor of 4, noted as a point on the ordinate of Figure 6 corresponding to the point B of manganese curve. In the present example, a steel having grain size 7 containing 0.50% carbon and 0.90% manganese, and nothing else, would just harden all the way through when subjected to an ideal quench in a size of 0.24 inch multiplied by 4, namely 0.96 inch, or nearly one inch diameter.

The further addition of 0.10% silicon introduces a multiplying factor of 1.10 corresponding to point C on the silicon curve of Figure 6. The 0.020% phosphorus and 0.029% sulphur introduce two more factors 1.05 and 0.98, respectively, as determined by points D and E respectively on the phosphorus and sulphur curves on the diagram of Figure 7. The nickel content of 0.28 introduces a factor of 1.10, i. e., point F on the nickel curve in Figure 6; 0.30% chromium has a large factor of 1.70 determined at point G on the chromium curve of Figure 6; 0.05% molybdenum supplies a factor of 1.16 and 0.05% copper that of 1.02 determined respectively from point H on molybdenum curve and scaled from the line for nickel in Figure 6.

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Multiplying these factors for all elements present in steel results in a figure of 2.40 for the ideal diameter of steel having the above analysis and grain size and actual quenching and microscopic observation check the figure.

The numerical relations discussed above omit from consideration the existence of carbides as a separate phase. When carbides remain undissolved after quenching, the diagrams showing ideal critical diameter as a function of element content can indicate only a maximum possible hardenability. Hardening actually obtained may be much less, depending on the percentage of carbides remaining undissolved. This feature is illustrated by the hatched areas above the chromium and vanadium curves of Figures 6 and 7.

The method of the present invention offers a solution to a problem of great importance and long standing, i. e., prediction of hardening characteristics of any steel without actual quenching. It offers a true measure of hardenability independent of quenching conditions, is accurate by resting on precise measurements of actual critical size, is readily applicable to the extremes of the hardenability range, is related to the already familiar depth of hardening method of testing, and is conveniently visualized for practical application through the conception of hardening throughout.

It is believed that many alternates can be evolved around the teachings of this invention without departing from the spirit thereof as recited in the appended claim.

This application is a division of application Serial No. 448,453, filed June 25, 1942.

I claim:

A method of determining the hardenability of steel, comprising the steps of making a series of steels having the same basic composition but varying in the content of one alloying element, making cylindrical quenching specimens of said steels in various sizes, quenching said specimens under identical conditions, and measuring the diameters of the largest specimen of each of said steels which is hardened throughout, i. e., the critical diameter at which the quenched specimen is characterized by the absence of a relatively soft core within an external hardened case, thereby obtaining a relation between such critical diameter and the content of said alloying element giving the hardenability factor of the latter, then repeating the procedure set forth above for various elements entering into the composition of steel, the hardenability of a steel containing known amounts of the several elements being given by the product of the hardenability factors corresponding to such amounts of all the elements present in the steel.

MARCUS A. GROSSMANN.

REFERENCES CITED

The following references are of record in the file of this patent:

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Number	Country	Date
822,527	France	Dec. 31, 1937

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Am. Soc. for Metals—Transactions, vol. 26, 75 1938, pages 1-37. (Copy in Div. 3.)

Certificate of Correction

Patent No. 2,559,016

July 3, 1951

MARCUS A. GROSSMANN

It is hereby certified that error appears in the printed specification of the above numbered patent requiring correction as follows:

Column 4, line 64, for "relates" read *related*; column 5, line 35, for "obtain" read *obtained*; column 7, lines 39 and 40, for "1.10 silicon" read *1.10% silicon*; line 47, for "of 50 per cent" read *to 50 per cent*;

and that the said Letters Patent should be read as corrected above, so that the same may conform to the record of the case in the Patent Office.

Signed and sealed this 25th day of September, A. D. 1951.

[SEAL]

THOMAS F. MURPHY,
Assistant Commissioner of Patents.