Hardness of Tempered Martensite in Carbon and Low-Alloy Steels

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This paper presents the results of a systematic study of the effect of carbon, manganese, phosphorus, silicon, nickel, chromium, molybdenum, and vanadium on the hardness of martensite in low to medium carbon steels tempered for one hour at 100°F (56°C) intervals in the range 400 to 1300°F (204 to 704°C). Results show that the as-quenched hardness depends solely on carbon content. On tempering, the effect of carbon on hardness decreases markedly with increasing tempering temperature. Studies of carbon-0.5 manganese steels showed that the incremental increase in hardness from 0.5 pct manganese after a given tempering treatment was independent of carbon content. Based on this result, studies of the effects of the other alloying elements were made using a 0.2 or 0.3 pct carbon, 0.3 to 0.5 pct manganese steel base composition. The hardness of the resulting tempered martensite was assumed to be due to a given alloy addition, and when two or more alloying elements were added, their effects were assumed to be additive.

Each of the seven alloying elements increased the hardness of tempered martensite by varying amounts, the increase being greater as more of each element was present. Nickel and phosphorus have substantially the same effect at all tempering temperatures. Manganese has essentially the same hardening effect at any temperature in the range 700 (371°C) to 1300°F; silicon is most effective at 600°F (316°C), chromium at 800°F (427°C), molybdenum at 1000 to 1100°F (538 to 592°C), and vanadium at 1200°F (649°C).

Using the data obtained, a procedure is established for calculating the hardness of tempered martensite for carbon and alloy steel compositions in the range studied and for any combination of tempering time and temperature.

THE importance of developing a tempered martensite structure to provide strength and toughness in high-strength steels has long been recognized.[1] For a steel of given carbon content and alloy composition, the final subcritical heat treatment (tempering treatment) establishes the hardness of the steel and for tempered martensites, the hardness can be used to estimate tensile strength. In addition to carbon and alloy content, such factors as the prior austenite grain size influence strength. This last-mentioned factor is beyond the scope of the present paper.

Although there has been a considerable body of information published over the past forty years on the effect of carbon and the individual alloying elements on the hardness of tempered martensite,[2-6] these investigations have dealt mainly with medium carbon steels, have been cumbersome to use, and have not fully accounted for secondary hardening effects. The present paper describes the results of a coordinated study to evaluate the effect of carbon and alloying elements on the hardness of quenched and tempered low carbon steels. Using the procedures prescribed in the paper, one can calculate the hardness and, in turn, the strength that will be achieved from a given tempering treatment for steels with compositions lying within usual ranges for AISI carbon and alloy steels.

MATERIALS AND EXPERIMENTAL WORK

Iron-carbon alloys and high cleanliness steels were prepared by vacuum induction melting 35 pound (16 kg) heats of electrolytic iron, graphite and pure ferroalloys. Each 35 pound heat was split into two ingots, the second of which contained twice the amount of the element of interest added to the first.

Ingots were hot-rolled to 0.25 in. thick (6.3 mm) plate. A portion of each hot-rolled plate was then cold-rolled to 0.1 in. thick (2.5 mm) strip or, in a few instances, to 0.05 in. thick (1.3 mm) strip. Specimens 0.5 in. (12.7 mm) square were taken from the cold-rolled strip for heat treatment.

The composition of the steels used in this investigation with respect to the significant elements can be determined by reference to Table I. Other than the principal elements, the amount of any minor element present was always less than 0.005 pct and its effect was considered insignificant.

Specimens from each series of steels made up of graded amounts of one alloying element were heat-treated as a group, simultaneously, to avoid any possibility of variation in heat treatment affecting the data for a given element. All specimens were austenitized for 10 min at 1700°F (927°C) and quenched in 6 pct NaCl brine. Except for the higher carbon steels, the as-quenched samples contained essentially 100 pct martensite. Steels with a 0.50, 0.72, or 0.98 pct carbon contained retained austenite in amounts of 3, 7, and 13 pct, respectively. Slack quenching tended to occur in the low carbon Fe-C alloys, and this tendency was minimized by reducing specimen thickness from 0.1 to 0.05 in. (2.5 to 1.3 mm). Tempering, always for 1 h, was done in a circulating-air furnace for

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Table I. Levels of Significant Elements in Iron-Carbon Alloys and High Cleanliness Steels Investigated

Alloy Series	Levels of Element Varied, Pct
Carbon*	0.12, 0.20, 0.42, 0.50, 0.72, 0.98
0.5Mn—Carbon*	0.08, 0.20, 0.42, 0.58, 0 78
0.2C—Manganese*	0.35, 0 64, 0.90, 1.22, 1 66, 1.95
0.2C—0.5Mn—Phosphorus*	0.002, 0.06, 0.28
0 19C—0.53Mn—Silicon*	0.09, 0.29, 0.56, 0.85
0.18C—0.30Mn—Nickel*	0.20, 0.27, 0.80, 1.55
0.19C—0.3Mn—Chromium*	0.1, 0.18, 0.40, 0.63
0.18C—0.3Mn—Molybdenum*	0.06, 0.12, 0.17, 0.41
0.19C—0.5Mn—Vanadium*	0.02, 0.052, 0.075, 0.18

*Element varied.

temperatures below 700°F (371°C) and in lead for temperatures at and above 700°F.

The austenite grain size was determined for one set of specimens of each series and found to be in the range 4 to 6 ASTM. This variation in grain size was found to have an insignificant effect on the hardness of tempered martensite.

After heat treatment, each set of specimens was mounted edgewise (using an unheated polymer in the as-quenched condition and bakelite when tempered), ground to remove at least 0.06 in. (1.5 mm) from the exposed surface and polished. Three or more diamond pyramid (HV) hardness measurements with 20 kg load were made for each specimen. In those few instances, where all three hardness readings were not identical, additional hardness measurements were taken after regrinding and polishing.

The microstructure of all specimens was examined after etching in picral and nital solutions. Photomicrographs were taken to illustrate the effect of each element on microstructure.

RESULTS

Fe-C Alloys

Results for iron-carbon alloys with carbon content ranging from 0.12 to 0.97 pct, are shown graphically in Fig. 1. The measured hardness of each specimen is represented by a point, and a smooth curve is drawn through the points for each tempering temperature to show the hardness at any carbon content.

The relation between carbon content and hardness for as-quenched martensite is somewhat lower than the relation shown by Bain and Paxton[2] but agrees remarkably well, as seen in Fig. 1, with that obtained by Jaffe and Gordon[5] for samples water quenched and then cooled to −320°F (−196°C). The hardness of as-quenched martensite of a particular carbon content was not changed significantly as a result of adding manganese or other alloying elements. Thus, the curve for as-quenched martensite is the maximum hardness attainable by quenching to martensite in all the carbon and low alloy steels investigated, and the alloy content apparently did not change the retained austenite content of the steels sufficiently to affect the as-quenched hardness. However, the curves for all tempered specimens are higher when alloying elements are added to Fe-C alloys. The curves of Fig. 1 thus serve as a base to which the effect of the alloy in
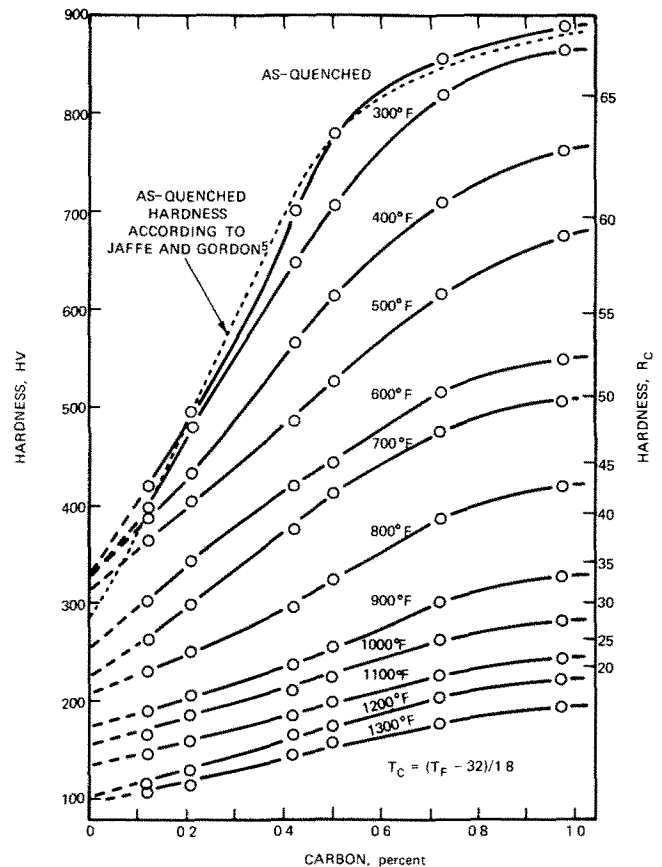

Fig. 1—Hardness of tempered martensite in iron-carbon alloy.

resisting softening on tempering can be added. The resistance to softening thus can be shown as an increase in the hardness (ΔHV) over that which would be obtained by tempering an Fe-C alloy. When referring to the effect of various alloying elements on tempering response in the figures and discussion, the term increase in hardness (ΔHV) due to the alloy will be understood to be a measure of the resistance to softening imparted by the alloying element.

Figure 2 shows typical micrographs of specimens chosen to illustrate the effect of carbon on quenched martensite and on martensite tempered one hour at 1300°F (704°C). In the as-quenched condition, so-called lath martensite is present at 0.12 pct carbon and plate martensite at 0.42 and 0.97 pct carbon. Somewhere between 0.12 and 0.42 pct carbon, the structure changes from lath to plate martensite; the transition is probably gradual, since the hardness curve exhibits no discontinuity in hardness.

When Fe-C alloys are tempered at 1300°F, hardness does not increase greatly with carbon content (Fig. 1). Figure 2 indicates that with increasing carbon content, the cementite particles become larger rather than more numerous; thus, the mean distance between particles, which principally determines hardness, changes relatively little.

Fe-0.5Mn-C Alloy

A series of five alloys, all containing 0.5 pct manganese with carbon varying in the range 0.07 to 0.78 pct, was investigated to determine the quantitative

effect of manganese on the hardness of tempered martensite in alloys with different carbon contents. The data points connected by dashed lines in Fig. 3 shows the results for Fe-0.5Mn-C alloys at tempering temperatures of 600, 800, 1000, and 1200°F (316, 427, 538, and 649°C). The solid-line curves are for Fe-C alloys transposed from Fig. 1.

After tempering at 400°F (204°C), the points for the Fe-0.5Mn-C alloys lie on the curve for Fe-C alloys. Thus, manganese had no effect on the hardness of martensite tempered at 400°F. At higher tempering temperatures, the presence of manganese resulted in higher hardness after tempering. The fact that the corresponding curves for a given tempering tempera-
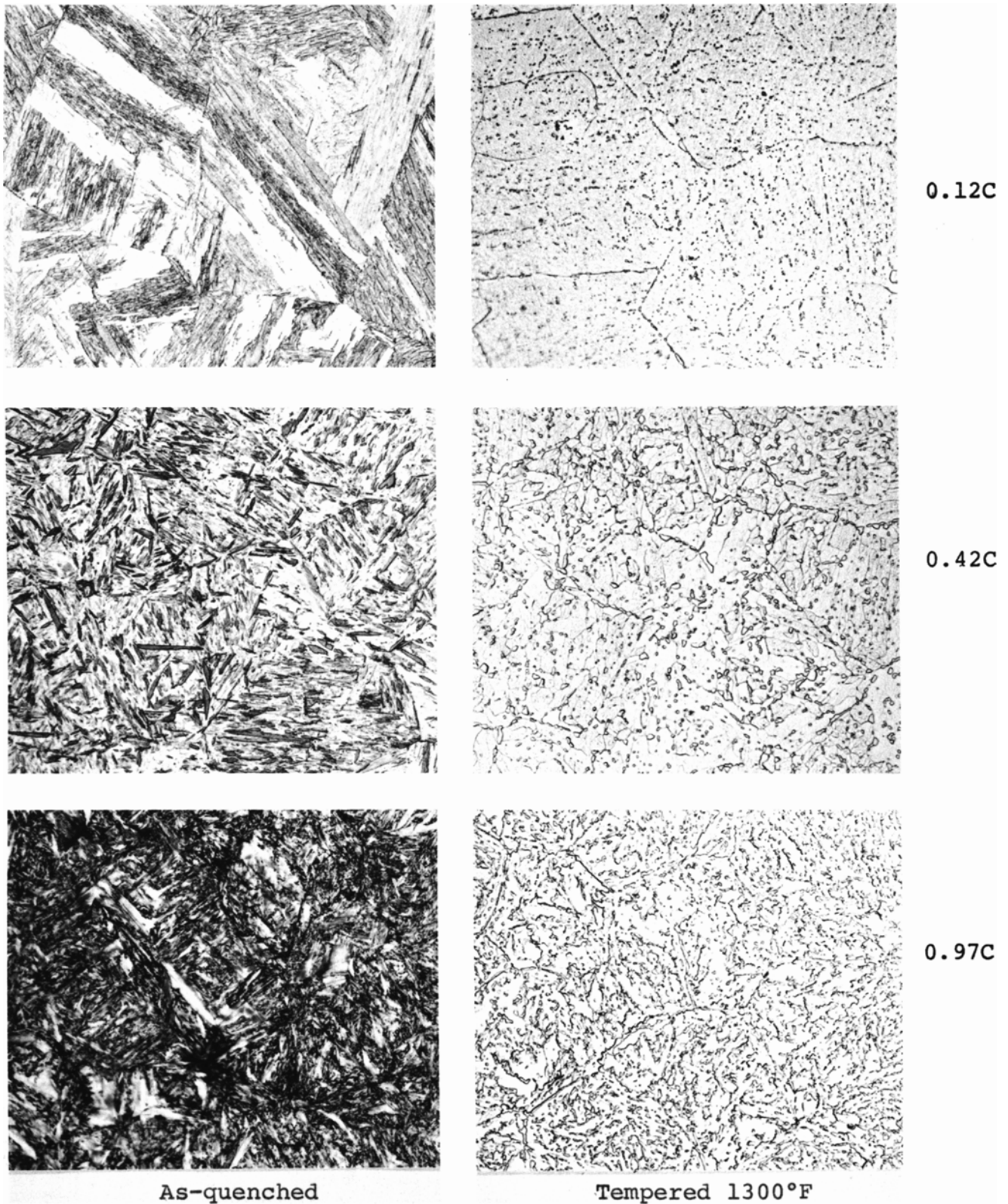
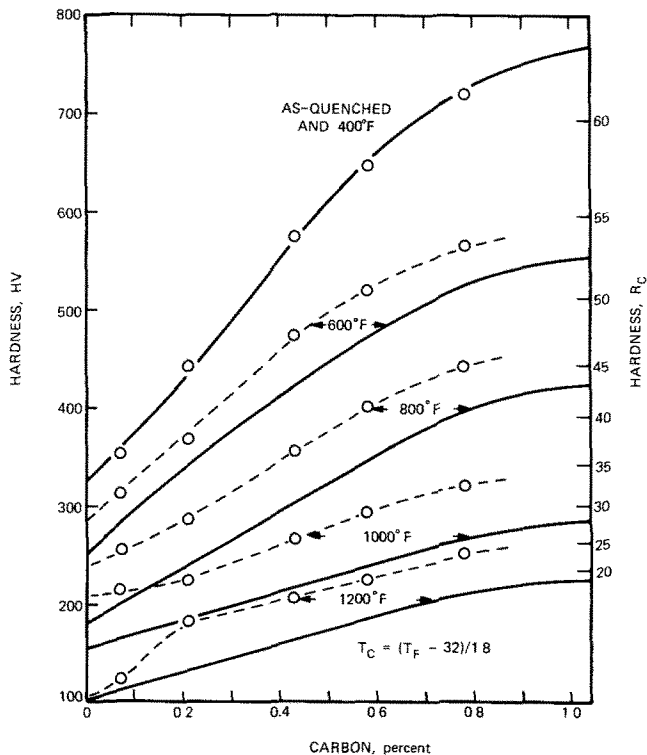Fig. 2—Effect of carbon content on the microstructure of Fe-C alloys. Magnification 500 times.

Fig. 3—Effect of 0.5 pct manganese on the hardness of tempered martensite in steels containing various amounts of carbon.
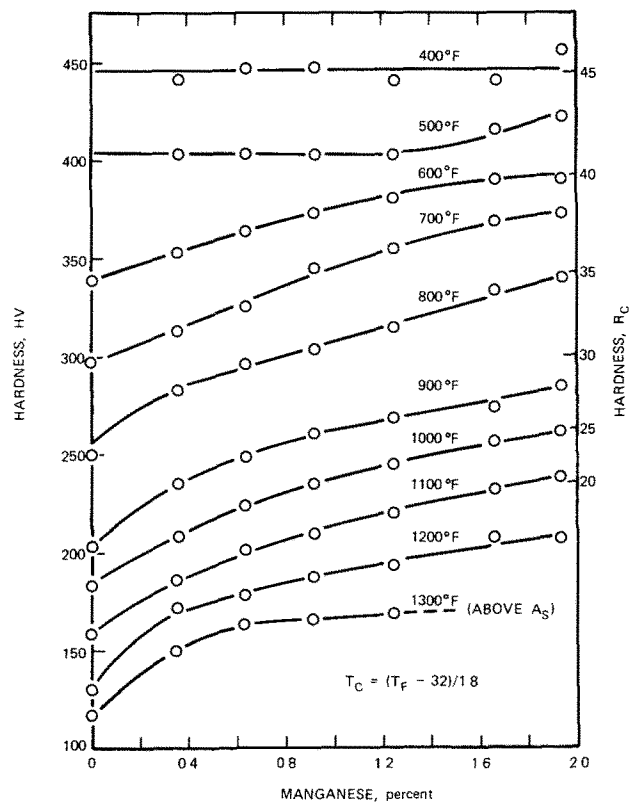

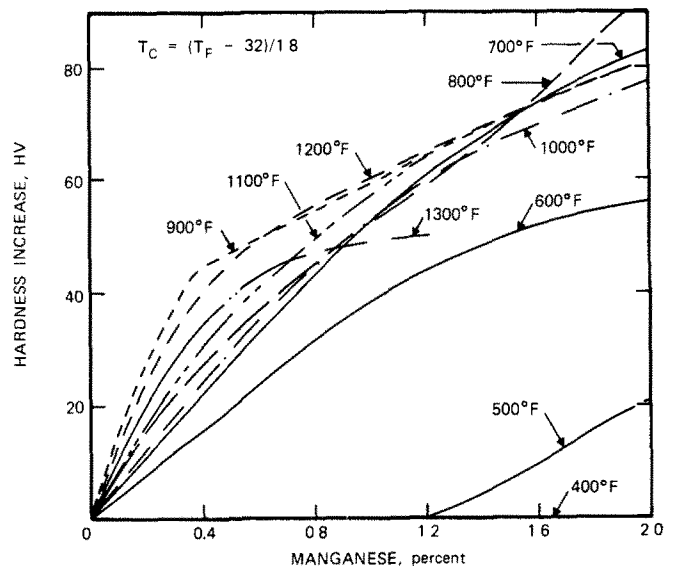Fig. 4—Hardness of tempered martensite in 0.2 pct carbon steels containing different amounts of manganese.

Fig. 5—Increase in hardness due to manganese in 0.2 pct carbon, quenched and tempered steels.

ture are very nearly parallel indicates that for a given tempering temperature, 0.5 pct manganese had substantially the same hardening effect at all carbon contents.* These results offer some assurance that the

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*The low hardness value for the 0.07 pct carbon alloy tempered at 1200°F (649°C) was due to atypical, exaggerated ferrite grain growth in this specimen

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effect of other alloying elements may also be independent of carbon content. In the work that follows, a 0.2 pct carbon steel is used as a base and the assumption is made that the effect on hardness of a given alloy addition would be independent of the carbon content. This assumption, which might be expected to be rather tenuous for strong carbide formers, was tested later by comparing calculated and actual hardnesses for different steels tempered at different tempering temperatures and found to be reasonably valid within the composition ranges investigated.

Effect of Different Amounts of Manganese

Results for six pure steels containing 0.2 pct carbon and different amounts of manganese in the range 0.35 to 1.97 pct are given in Fig. 4. The points for zero manganese were taken from the earlier results for Fe-C alloys (Fig. 1). The data show that when tempered at 400°F (204°C), increasing manganese content did not result in a higher hardness than that of the Fe-C alloy tempered at 400°F (204°C) but substantially higher hardnesses were obtained for the manganese containing alloys at tempering temperatures of 600°F (316°C) and above. Note that the curve for 1300°F (704°C) tempering ends at about 1.2 pct manganese because with more than this amount of manganese, the A_1 temperature is exceeded.

The results are summarized in a more general and

convenient form in Fig. 5 by plotting the increase in the tempered hardness of the 0.2 pct carbon steel resulting from various manganese additions. The effect of manganese on the hardness of tempered martensite is shown to increase from zero at 400°F (204°C) in a regular manner with tempering temperature to 800°F (427°C). In the region from 800°F to 1300°F, the hardness increase varies about an average value. The variation is ±10 HV Vickers hardness numbers in the region of 0.4 pct manganese and the amount of variation is a minimum at 1.6 pct manganese.

As manganese increased, the appearance of the mi-

Fig. 6—Effect of manganese on the microstructure of martensite tempered at 1200°F (649°C) for 1 h. Magnification 455 times.
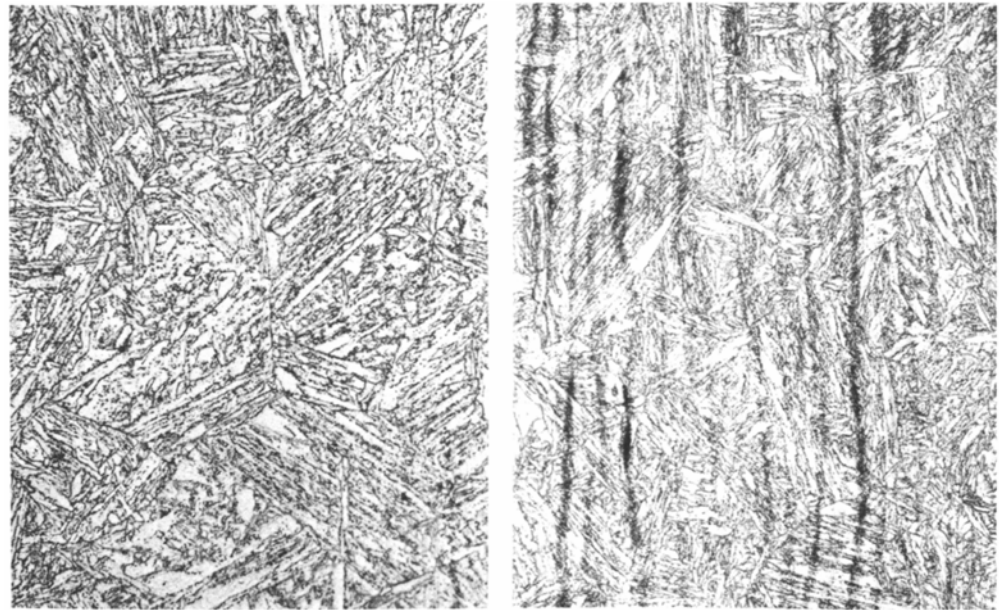
0.35Mn   1.97Mn

crostructure of tempered martensite changed noticeably. This change can be illustrated by comparing the low and high manganese steels tempered at 1200°F (649°C), Fig. 6. As manganese increased, 1) the martensitic appearance was retained to a greater degree, 2) the carbides, when examined at high magnification, were found to be smaller and more numerous, and 3) the microstructural banding was accentuated. These changes suggest that manganese increases the hardness of tempered martensite principally by retarding the coalescence of carbides, and thus provides a resistance to grain growth in the ferrite matrix. The combination of more and smaller carbides and an apparent lower state of recovery of the martensite (finer packets of ferrite), causes the observed substantial increase in the hardness of tempered martensite as the percentage of manganese in steel increases.

Effects of Other Alloying Elements

In a manner similar to that used in determining the effect of manganese, the effect of incremental amounts of the alloying elements, P, Si, Ni, Cr, Mo, and V on the response to tempering were determined and the increase in hardness over that of an Fe-C alloy tempered for 1 h at the same temperature was determined for each increment in alloy and for each of the tempering temperatures. Families of curves similar to those shown in Fig. 5 were plotted for each alloying element. These plots were used to examine the effect of the various alloying elements on tempering response. However, the effects are not shown in this form but are shown later in Figs. 8 through 17, where for a given tempering temperature, the increase in hardness observed for each of the alloying elements is plotted as a function of the alloy content.

Effect of Phosphorus. Similar data were obtained for three levels of phosphorus (0.002, 0.064, or 0.28 pct phosphorus) in a 0.2 pct carbon-0.5 pct manganese steel. Phosphorus increased the hardness of tempered martensite at all tempering temperatures ex-

cept 400°F (204°C). For various tempering temperatures, the increases in hardness due to phosphorus were found to all scatter about a single curve. Thus, phosphorus may be considered to have the same effect at all tempering temperatures in the range 500 to 1200°F (260 to 649°C).

Metallographic examination showed that phosphorus had little effect on carbide size, and, therefore, phosphorus was assumed to increase the hardness of tempered martensite principally, if not entirely, by solid-solution hardening of the ferrite matrix.

Effect of Silicon. Similar data were obtained for a series of 0.19C-0.5Mn steels containing graded amounts of silicon as indicated in Table I. Silicon in-
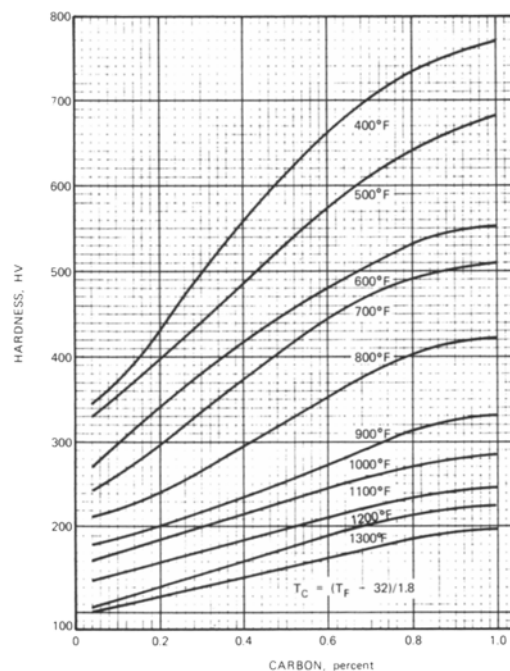

Fig. 7—Chart showing hardness of tempered martensite in Fe-C alloys.
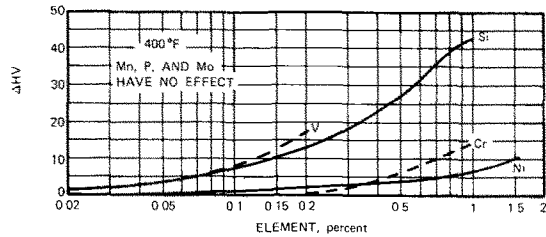
Fig. 8—Effect of elements on the hardness of martensite tempered at 400°F (204°C) for 1 h.
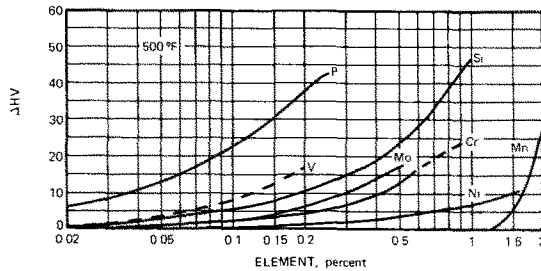

Fig. 9—Effect of elements on the hardness of martensite tempered at 500°F (260°C) for 1 h.
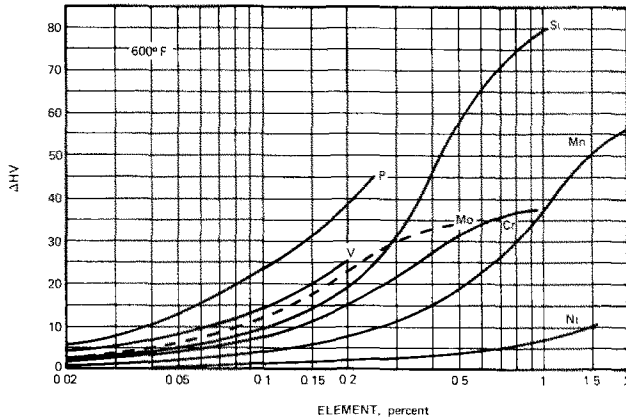

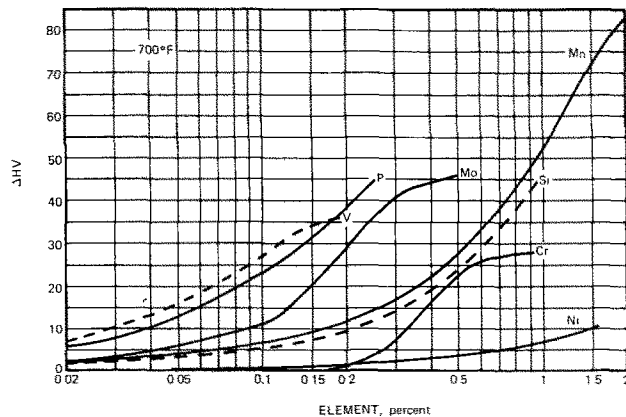Fig. 10—Effect of elements on the hardness of martensite tempered at 600°F (316°C) for 1 h.

Fig. 11—Effect of elements on the hardness of martensite tempered at 700°F (371°C) for 1 h.
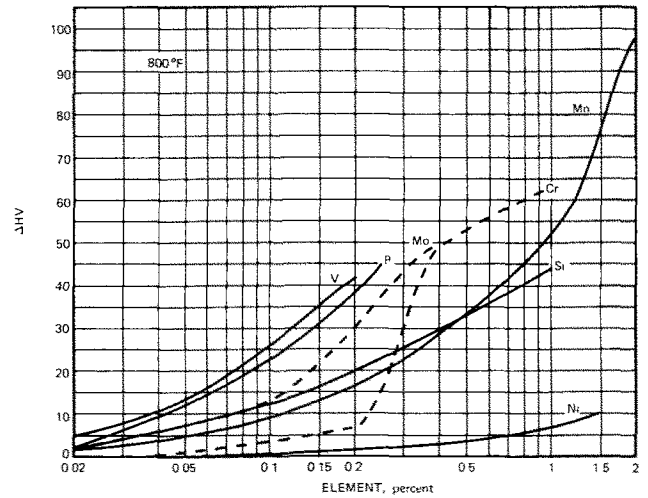

Fig. 12—Effect of elements on the hardness of martensite tempered at 800°F (427°C) for 1 h.
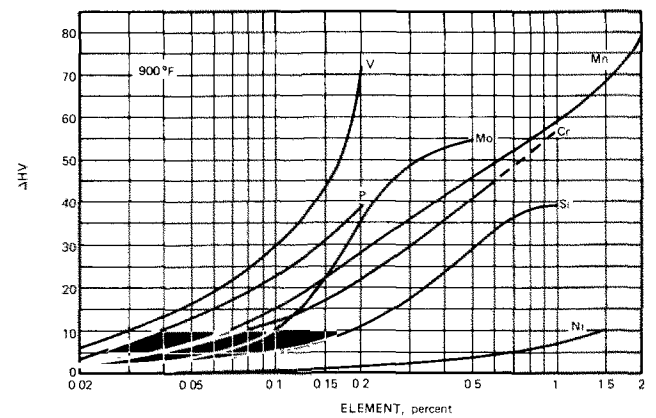

Fig. 13—Effect of elements on the hardness of martensite tempered at 900°F (482°C) for 1 h.
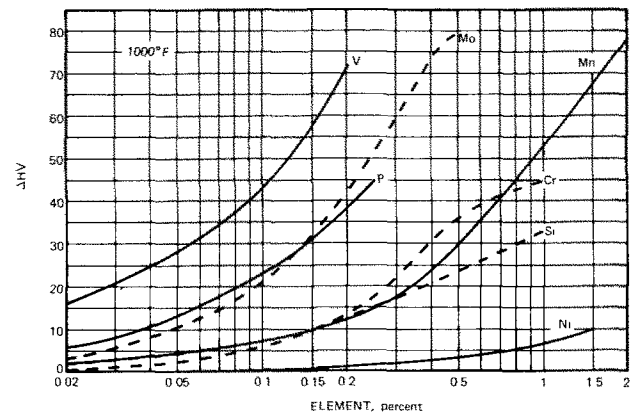

Fig. 14—Effect of elements on the hardness of martensite tempered at 1000°F (538°C) for 1 h.

creased the hardness of tempered martensite at all tempering temperatures.

Silicon was found to have a much greater effect at 600°F (316°C) than at other tempering temperatures. This result is in agreement with the well-known effect of silicon in inhibiting the conversion of epsilon carbide to cementite, a change that occurs at about 600°F.[7]

The microstructure of tempered martensite was noticeably affected by adding 0.86 pct silicon. Metallographic examination of samples containing 0.09 Si and 0.86 Si tempered at 1200°F (649°C) showed that the carbides were smaller and the ferrite tended to be divided into smaller lath-like regions (packets) in the 0.86 Si steel, which probably explains most of the hardening effect of silicon; however, silicon also probably increases the hardness of tempered martensite by solid-solution hardening.

Effect of Nickel. Study of the effect of nickel on 0.18C-0.3Mn steels showed that nickel has a relatively small effect on the hardness of tempered martensite which is essentially the same at all tempering temperatures.
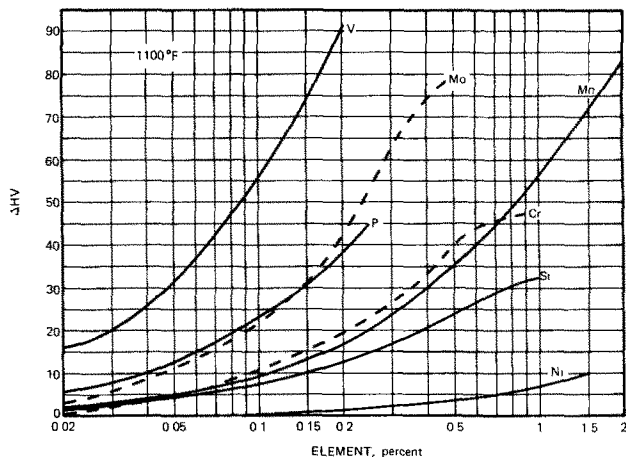

Fig. 15—Effect of elements on the hardness of martensite tempered at 1100°F (592°C) for 1 h.
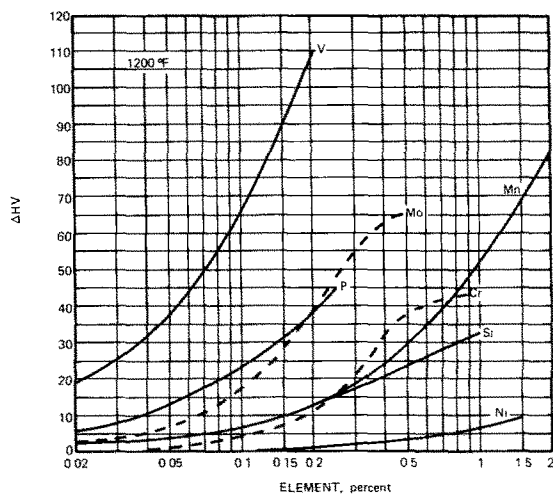

Fig. 16—Effect of elements on the hardness of martensite tempered at 1200°F (649°C) for 1 h.
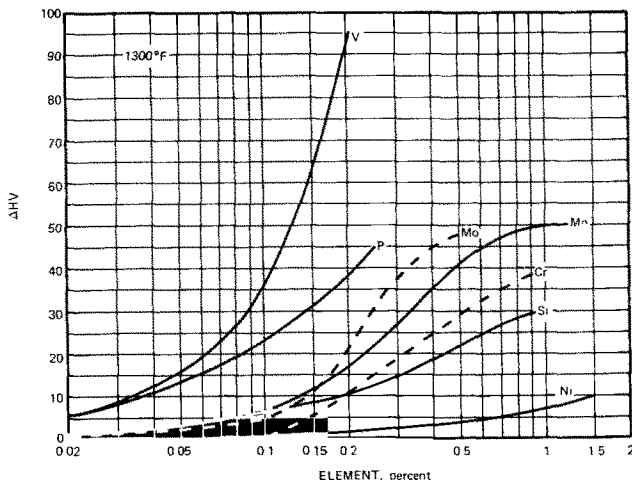

Fig. 17—Effect of elements on the hardness of martensite tempered at 1300°F (704°C) for 1 h.

The increase in hardness resulting from nickel for any tempering temperature can be quantitatively expressed by a single line drawn from zero for a nickel free steel to an increase in hardness (ΔHV) of 10 points in diamond pyramid hardness for a steel containing 1.5 pct nickel.

In accordance with its smaller effect on the hardness of tempered martensite, nickel has no apparent effect on microstructure. The effect of nickel is probably due to weak solid-solution hardening.

Effect of Chromium. The effect of chromium in the range 0.10 to 0.63 pct was investigated in a 0.19C-0.3Mn steel. Chromium retards the tempering of martensite at all tempering temperatures. Obviously, the effect of chromium, which is the first strong carbide forming element to be discussed, is more complex than that of weak carbide formers (Mn) or noncarbide formers (P, Si, and Ni). The increased hardness due to chromium, weak at 400°F (204°C), increases to a maximum at 800°F (427°C), the temperature at which the alloy carbides produce maximum strengthening, and then decreases with increasing tempering temperature because the carbides coalesce.

Metallographic investigation showed that, in the higher chromium steels, carbides were smaller and more numerous and that the microstructure remained more acicular in appearance (finer packets) than in low chromium steels. Chromium in the percentage range investigated substitutes for some of the iron in cementite, and thus retards coalescence of carbides.

Effect of Molybdenum. Molybdenum, like chromium, is a strong carbide forming element that can be expected to produce substantially higher hardness than an Fe-C alloy when the alloys are tempered at higher temperatures. The effect of the molybdenum contents shown in Table I on tempering in a 0.15C-0.3Mn steel was determined.

At 400°F (204°C), molybdenum had no effect but increases in hardness were observed in increasing amount as the tempering temperature increased to 1000°F (538°C). At 1000 and 1100°F (592°C), the effect of molybdenum was the same, but the increase in hardness was lower when tempering at 1200°F (649°C). Molybdenum is a potent addition to steels quenched and tempered at 1000°F or above. It partitions to the carbide phase at elevated temperatures, and thus keeps the carbide particles small and numerous.

Effect of Vanadium. Because vanadium is a stronger carbide former than chromium or molybdenum, it can be expected to have a potent effect on the hardness of tempered martensite. Vanadium carbide forms in steel containing relatively small amounts of vanadium. The effect of the vanadium contents shown in Table I on tempering in a 0.19C-0.5Mn steel was determined.

The maximum increase in hardness, which occurred in specimens tempered at 1200°F, was considerably greater than that observed with other alloying elements, even though the maximum percentage of vanadium added was only 0.18 pct. The effect of vanadium increased steadily with increasing tempering temperatures up to 1200°F. Vanadium was also potent at 1300°F (704°C) (only slightly below A_1). The large effect of vanadium is probably due to the formation of an alloy carbide (V_4C_3 or VC), which replaces cementite type carbide at high tempering temperatures and persists as a fine dispersion up to the A_1 temperature.

ESTIMATION OF THE HARDNESS OF TEMPERED MARTENSITE FROM CHEMICAL COMPOSITION

The quantitative effect of the significant chemical elements (C, Mn, P, Si, Ni, Cr, Mo, and V) present in standard grades of carbon and low-alloy steels has been evaluated. The effect of other elements normally present but not evaluated can be ignored in most quenched and tempered steels. Sulfur is present in inclusions and aluminum is used in very small amounts. Some success has been achieved in estimating the hardness of tempered martensite from chemical composition, but the methods proposed[3-5] have been based on inadequate data, are largely empirical, and are rather complicated. It is therefore worthwhile to consider how the present data might be incorporated into a new, more reliable method of estimating the hardness of tempered martensite. Such a method would save much of the time and effort presently expended in conducting trials and would be helpful in selecting steel compositions for quenched and tempered steel products.

Ideally, the development of a general equation from which hardness could be calculated directly from chemical composition, tempering time, and tempering temperature, would be desirable. However, the large amount of data generated in the present study, the wide ranges in composition and temperature covered, and the complex tempering reactions occurring make the formidable task of developing such an equation of questionable merit. Accordingly, a more practical procedure is proposed in which the hardness of tempered martensite is estimated from a series of standard charts. The obvious starting point for such an estimate is with the data for Fe-C alloys. Carbon content has a large and basic effect and carbon is present in all steels. The hardness of Fe-C alloys varies greatly with carbon content at low tempering temperatures but much less so at high tempering temperatures; consequently, even the effect of carbon would appear to be too complex for simple mathematical formulation. The hardness of tempered martensite at any particular carbon content is therefore determined from a suitable chart. For this purpose, the curves of Fig. 1 for tempering temperatures of 400°F (204°C) and above were drawn on a chart with numerous coordinate lines to aid in reading hardness values (Fig. 7). Tempering curves are given for 100°F (56°C) intervals, and although interpolation at intermediate temperatures is possible, it is considered preferable to read the curves directly and estimate hardness at intermediate tempering temperatures as a final step.

To estimate the increase in hardness produced from elements other than carbon, a set of quantitative "read-off" charts is required; the set consists of one chart for each tempering temperature. These charts are presented in Figs. 8 through 17. On these charts, the data is presented on a semilogarithmic scale to permit accurate readings for the percentages of elements present in relatively small amounts. Each element, unless it had no effect at a particular tempering temperature, is represented by a curve on each chart.

The use of the charts for estimating the hardness of tempered martensite from chemical composition is rather obvious. For a given steel composition being considered, the hardness, for example, at 1000°F (538°C) tempering temperature is the hardness of the Fe-C alloy with corresponding carbon content tempered at 1000°F plus all the ΔHV values for each of the other significant elements present in the steel. Thus,

Estimated HV (1000°F) = HV (from Fig. 7)

$$+ \Delta HV_{Mn} + \Delta HV_P + \Delta HV_{Si}$$
$$+ \Delta HV_{Ni} + \Delta HV_{Cr} + \Delta HV_{Mo}$$
$$+ \Delta HV_V \text{ (all from Fig. 14).}$$

The ΔHV value for any element not present in the steel for which the tempered hardness is being estimated, of course, drops out of the formula. Therefore, estimation by this method is a matter of simple addition and can be done quickly and easily.

The estimated hardness values for each tempering temperature represented by a chart (100°F or 56°C intervals in the range 400 to 1300°F or 204 to 704°C) can be plotted to give an entire tempering curve of hardness vs tempering temperature. The resulting curve permits interpolation for hardness at any tempering temperature between the 100°F intervals used in constructing the chart. Often, an estimator will be interested only in the hardness after tempering in a limited range, for example 1000 to 1200°F (538 to 649°C), in which case fewer calculations are required.

COMPARISON OF ESTIMATED WITH EXPERIMENTALLY DETERMINED TEMPERING CURVES

A considerable number of experimentally determined tempering curves are available from earlier work,[4] and to test the validity of the assumptions made regarding interactions between alloying elements, tempering curves for different commercial grades of steel may be calculated using the proposed charts and compared with those determined by direct measurement. The experimentally determined curves to be compared were developed from hardness measurements made on small specimens fully quenched to martensite and tempered for one hour.

Figures 18(a) and (b) provide comparisons of estimated hardness values with those of the experimentally determined tempering curve of two grades of carbon steel (1026 and 1080). In these figures, as well as in others to follow, the estimated hardness value at each 100°F interval in tempering temperature is shown as a point for comparison with the directly measured tempering curve. In the two steels, estimated hardness values lie reasonably close to the measured curve. The inherent variability in heat treating and hardness testing is such that a variation of at least $\pm 1 R_C$, or about ± 10 HV, can be considered to be the best agreement that can be expected; most of the estimated points are within this range relative to the measured curve. For these carbon steels, the estimated hardness is generally on the low side.

A similar comparison of estimated and experimentally determined tempering data for 8650 steel is given in Fig. 19. The trend in this steel is for the estimated hardness values to be on the high side with respect to the measured curve. Nevertheless, a smooth

curve, if drawn through the estimated points, would be reasonably close to the measured curve.

Data for a vanadium containing grade of medium-carbon, low alloy steel (AISI 6145 steel) is shown in Fig. 20. Above 1000°F (538°C), the estimated values for this steel are considerably higher than measured values. This is in the tempering range where vana-

dium was found to have its greatest effect. The disagreement between the calculated values and the experimental values in this range is attributed to incomplete solution of vanadium in austenite in the steel used to obtain the experimental tempering curve.[4]
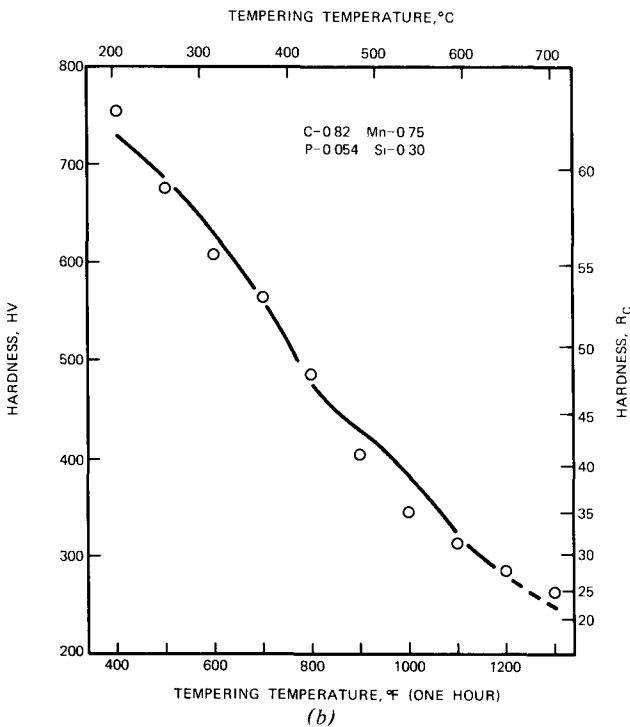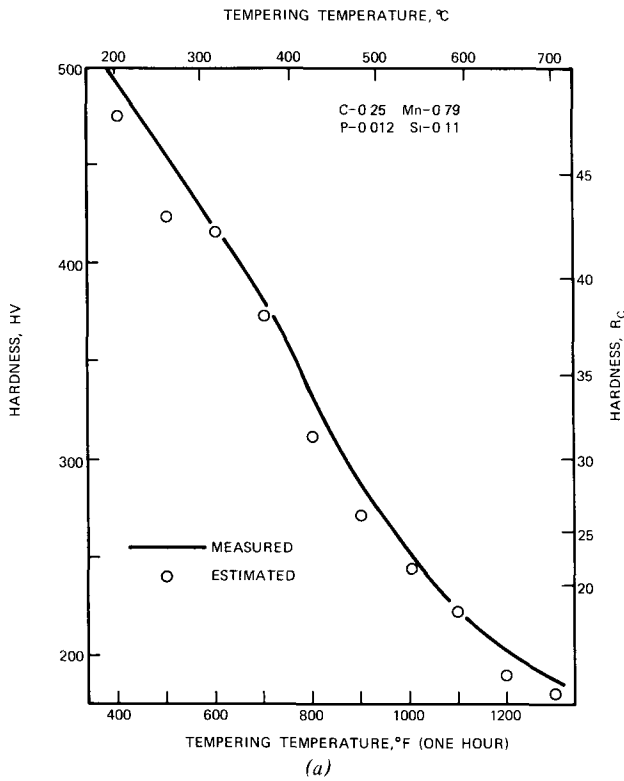

Fig. 18—(a) Comparison of measured and estimated hardness of tempered martensite in an AISI 1026 steel. (b) Comparison of measured and estimated hardness of tempered martensite in an AISI 1080 steel.
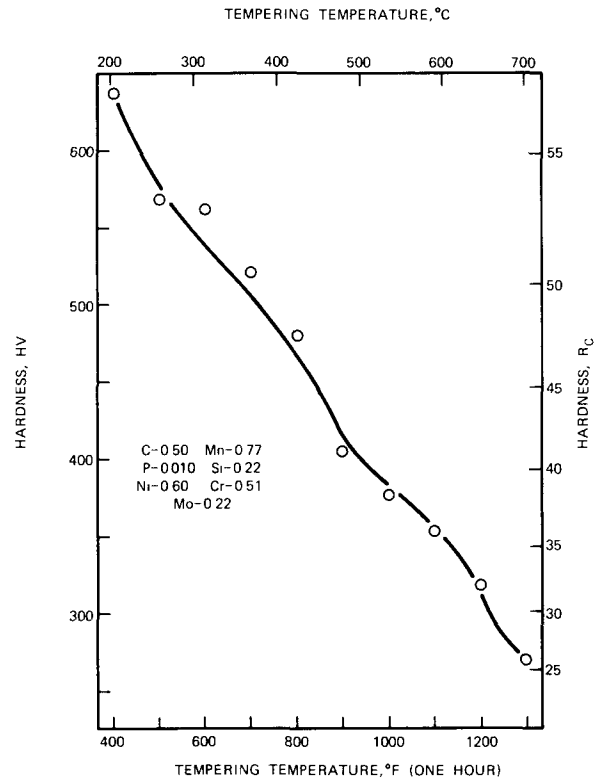

Fig. 19—Comparison of the measured (curve) and estimated (points) hardness of tempered martensite in an AISI 8650 steel.
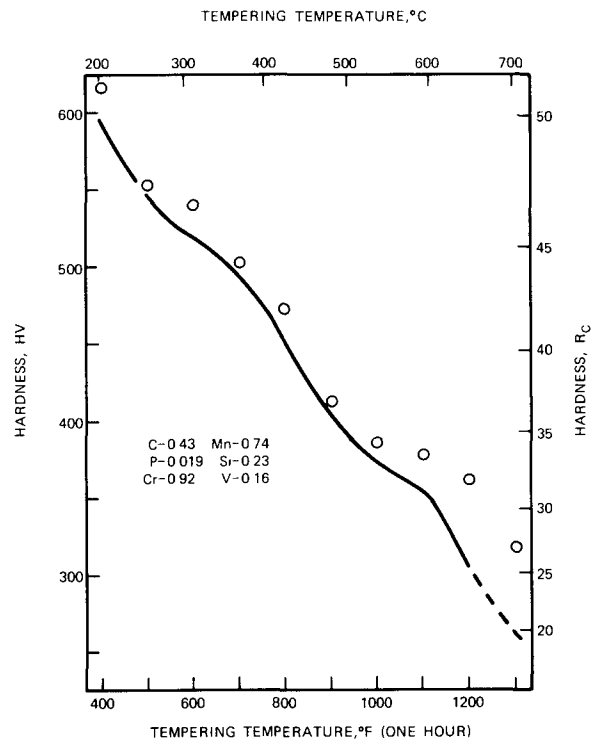

Fig. 20—Comparison of the measured and estimated hardness of tempered martensite in AISI 6145 steel.

The method of estimation, developed by using an 0.2 pct carbon steel, appears to be as satisfactory for medium and high carbon steels as for low carbon steels. This indicates that the quantitative effect of each of the alloying elements is independent of carbon content, at least over the 0.2 to 0.8 pct carbon range investigated. Estimated hardness values are least reliable for 400 to 600°F (204 to 316°C) tempering, although for some steels, they agreed well with measured values. In this tempering range, hardness would logically be least predictable from chemical composition because other factors are probably important. For example, when martensite is tempered below 600°F (316°C), retained austenite is usually not transformed, and quench tempering effects occur. Furthermore, 400 (204°C) to 600°F is the range in which epsilon is converted to cementite type carbide. These changes are affected by such variables as austenitizing temperature, specimen size, and severity of the quench.

No attempt has been made to establish the predicted error of this technique for calculating the hardness of tempered martensite, but the results given in Figs. 18 through 20 should provide the reader with an appreciation of the magnitude of the error that might be expected. In general, the accuracy with which the hardness of tempered martensite can be estimated from chemical composition by the method developed in this investigation is good and the method is easier to use and more reliable than earlier methods of estimating the hardness of tempered martensite from chemical compositions.

Conversion to Other Tempering Times

In this investigation, all hardness values, experimentally determined as well as estimated, are for a tempering time of 1 h. Such data are easily converted to a hardness value for any other tempering time through the use of the so-called tempering parameter.[4,8] A chart, Fig. 21, reproduced from an earlier study,[4] makes it possible to determine the hardness for tempering treatments either shorter or longer than 1 h. The basis for the conversion is that all combinations of tempering temperature and tempering time having the same parameter value will have essentially the same hardness. Thus, the chart is used by locating the 1 h tempering treatment and reading vertically up the constant-parameter ordinate line for times greater than one hour and down the same ordinate for times less than one hour. In this way, the tempering curve for any other desired tempering time, or any portion thereof, can be determined from the one-hour tempering curve.

Hardness Conversion

The method proposed for estimating the hardness of tempered martensite yields a diamond pyramid hardness (HV) number rather than the more common Rockwell C scale (R_C) number. Hardness measurements were made with the diamond pyramid hardness tester because this method is more precise and because the same scale encompasses both very hard and very soft steel. An HV hardness increase (ΔHV) due to an alloy addition cannot be shown as an equiva-
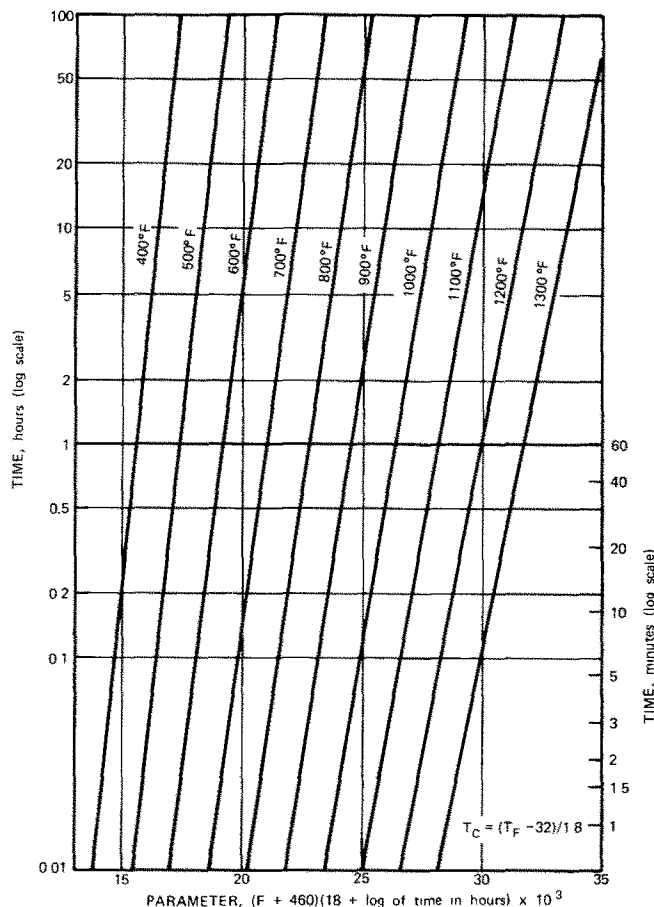

Fig. 21—Chart showing relationship of tempering parameter to temperature and time.

lent R_C hardness increase on an auxiliary scale on the charts because the R_C increase value varies with the hardness of the base steel. Therefore, all estimation is made in terms of HV hardness, and to convert the resulting estimated HV hardness to the more common R_C, or Bhn, or R_B values, a conversion chart is required.

Extrapolation

Based on the comparisons of measured and estimated hardnesses of tempered martensite in several alloy steels, alloying element interaction effects were not strong enough to be significant, probably because the maximum amount of each element considered was limited to the amount present in most AISI low alloy steels. This result, however, provides no assurance that extrapolating the composition range, for purposes of estimation, beyond that given in Figs. 8 through 17, will be reliable.

The method proposed for estimating the hardness of tempered martensite from chemical composition is valid only for steel quenched to martensite. Steel products that contain ferrite or pearlite (slack quenched) will usually be softer than the estimated value, especially at low tempering temperatures. In a steel product that, when tempered, is substantially softer than the estimated hardness value, the presence of slack quenched transformation products or undissolved carbides should be suspected.

SUMMARY

The hardness of quenched martensite and of tempered martensite was determined for a series of iron carbon alloys with carbon content varying over the range 0.1 to 1 pct. The quantitative effects of manganese, phosphorus, silicon, nickel, chromium, molybdenum, and vanadium was evaluated by adding gradual amounts of the element being studied to a steel containing about 0.2 pct carbon (when studying alloys other than manganese, the base composition also contained 0.3 or 0.5 pct manganese). The range of compositions investigated included the amounts and kinds of chemical elements present in most AISI grades of carbon and low alloy steel.

For martensite in the untempered condition, none of the alloying elements investigated increased hardness, but on tempering above 400°F (204°C), they all retarded softening. The increased hardness of the tempered steels due to alloying elements varied greatly, depending on the amount and kind of each element, and usually with tempering temperature. Only phosphorus and nickel had essentially the same effect at all tempering temperatures above 400°F (204°C). The greatest effect of silicon occurred when martensite was tempered at 600°F (316°C). The greatest effect of manganese occurred over the tempering temperature range of 800 to 1200°F (427 to 649°C). For the strong carbide forming elements, the tempering temperature of greatest hardness increase was 800°F (427°C) for chromium, 1000 or 1100°F (538 or 592°C) for molybdenum, and 1200°F (649°C) for vanadium. Vanadium was the most potent alloying element at tempering temperatures above 600°F (316°C).

On the basis of the data for Fe-C alloys, the quantitative effect of the amount of each alloying element present in a steel within the ranges investigated can be added to provide an estimate of the hardness of tempered martensite in a wide variety of carbon and alloy steels. Comparison of estimated tempering curves for a number of carbon and alloy steels with those determined experimentally indicated that the estimation is sufficiently accurate to be useful as a substitute for trial tempering treatments provided that the steel product is quenched to martensite free of any appreciable amount of ferrite or pearlite.

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