A New Method of Preparing Iso-Hardness Plots

V. Kumar and A.K. Patwardhan

A new approach has been used for the preparation of iso-hardness plots, which are very useful in the heat treating of metals and alloys. An alloy white iron containing ~6% Mn, ~5% Cr, and ~3% Cu was heat treated at 800, 850, 900, 950, 1000, and 1050 °C and soaked for 2, 4, 6, 8, and 10 h, respectively, at each of these temperatures followed by air cooling. It was observed that, although the hardness varied linearly with soaking time, its variation with soaking temperature was nonlinear. This can be represented as:

$$H = 98.285e^{2021.33/T} + (0.037 - 0.316 \times 10^{-4}T) \cdot t$$

where H is Vickers hardness; T is soaking temperature in K; and t is soaking time in seconds.
The variation in hardness has been discussed in light of microstructural changes that can take place upon heat treating.
A three-dimensional plot of hardness, soaking temperature, and time was prepared based on the above equation. It revealed that the variation in hardness on heat treating can be represented as a surface instead of lines, where the change in the slope of the surface reflects the various transformations occurring in the alloy system. This iso-hardness plot, consisting of contours of constant hardness, has been prepared by projecting the above-mentioned surface on the soaking temperature-time plane. The method of selection of heat treating parameters based on this iso-hardness plot is discussed.

Key words:
heat treating, iso-hardness, microstructure

1. Introduction

AN iso-hardness plot is the graphical representation of the effect of heat treating parameters (soaking temperature and soaking time) on hardness in the form of constant hardness lines. It can be extensively used as a tool to predict heat treating parameters to achieve the desired hardness in an alloy. Once prepared, it will help in decision-making by avoiding a large number of trials before selecting the optimum heat treating parameters, which will save time and, in turn, money.

Therefore, the aim of the present article is to provide the methodology to prepare such a plot. Finally, its usefulness is also discussed.

2. Experimental Procedure

The specimen alloy was air melted in a clay-bonded graphite crucible in a medium-frequency induction furnace and cast into ~25 mm diameter × 250 mm long cylindrical ingots in sand molds. The alloy was analyzed for carbon, sulfur, phosphorus, and silicon with a vacuum quantometer and for manganese, chromium, copper, phosphorus, and silicon with X-ray fluorescence spectrometry. The detailed composition is given in Table 1. Disc samples of ~15 mm height were sliced from the cylindrical ingots by making a 2 to 3 mm deep cut along the circumference on a silicon carbide cut-off wheel followed by hammering. They were ground to obtain parallel faces.

Heat treatments comprised of soaking at 800, 850, 900, 950, 1000, and 1050 °C for 2, 4, 6, 8, and 10 h followed by air cooling. These treatments were carried out in a muffle furnace whose temperature was controlled to ±5 °C.

Hardness measurements were taken on both the faces of a specimen on a Vickers hardness testing machine using a 30-kg load. A minimum of 20 impressions were taken on each specimen. Microstructural studies were carried out by optical metallography, X-ray diffractometry, EPMA, and differential thermal analysis (DTA). The analysis of data was done on a PC-AT/386 system.

3. Results and Discussion

The preparation of an iso-hardness plot involves (1) the understanding of the variation in hardness as influenced by heat treating parameters, (2) development of an interrelation between hardness and the heat treating parameters, and (3) preparation of the iso-hardness plot.

3.1 *Hardness as Influenced by Heat Treating Parameters*

To understand the variation in hardness with soaking temperature and time, it would be necessary to understand how heat treatment influences microstructure in an alloy system. Once this is established, it would be easy to develop an interrelation between hardness and the heat treating parameters.

The likely microstructural changes on heat treating can be divided into two groups, *i.e.*, changes during heating to the soaking temperature and changes during cooling to room temperature.

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Table 1 Alloy composition

Alloy	Composition, %						
	C	S	P	Si	Mn	Cr	Cu
B3…	2.90	0.068	0.280	1.80	6.2	4.7	2.84

Table 2 Effect of heat treating parameters on vickers hardness
As-cast hardness: 652 HV30

Soaking temperature, °C	Soaking time, h				
	2	4	6	8	10
800…	696	702	716	743	745
850…	569	578	615	621	642
900…	513	507	513	509	520
950…	492	500	496	485	489
1000…	477	422	380	378	359
1050…	399	364	357	293	261

3.1.1 *Structural Changes during Heating*

These structural changes can be enumerated as follows:

(1) A reduction in the volume fraction of massive carbides due to the presence of silicon and copper (attributed to their graphitizing tendency)

(2) An increase in the stability of austenite due to dissolution of additional alloying elements made available as a consequence of (1)

(3) A possible "rounding off" of the massive carbides and their being rendered discontinuous due to (1)

(4) Occurrence of a carbide transformation that would be governed by the nature of the phase diagrams

(5) Possible precipitation of carbides from austenite on prolonged soaking

3.1.2 *Changes during Cooling to Room Temperature*

The possible structural changes on cooling can be summarized with the help of the following equations:

Slow cooling (as during casting)

Austenite → pearlite/bainite + martensite (relative proportion of pearlite/bainite + martensite depending on alloy content) [1]

Carbide → unchanged or otherwise depending on carbide transformation [2]

Retention of austenite → depends on austenite stabilizing tendency of manganese and copper [3]

Final likely structure: Pearlite/bainite + martensite + (massive carbide) + (retained austenite) (?)

3.1.3 *Heat treated condition*

Lower temperatures: 800 and 850 °C

Austenite → austenite* + (dispersed carbide) [4]

Austenite* → martensite (extent of martensite depends on soaking period, i.e., less at lower soaking period and more at higher soaking period) [5]

Austenite* → austenite (depending on alloy content) [6]

Massive carbide → M_3C + other variants [7]

Dispersed carbide → dispersed carbide (coarse) [8]

Final likely structure: martensite + austenite + massive carbide + dispersed carbide

Intermediate temperatures: 900 to 950 °C

Austenite* → austenite (most probable at higher temperatures and soaking periods) [9]

Austenite* → austenite + martensite (volume fraction is small, which will further decrease with temperature and time) [10]

Dispersed carbide → dispersed carbide (coarse) [11]

Massive carbide → M_3C + other variants (volume fraction reduced) [12]

Likely final structure: austenite + dispersed carbide + massive carbide + some martensite (?)

Higher temperatures: 1000 and 1050 °C

Austenite* → austenite (matrix completely austenitic) [13]

Dispersed carbide → dispersed carbide (coarse) possible dissolution at higher soaking period(s) and temperature(s) [14]

Massive carbide → M_3C + other variants (M_7C_3) (volume fraction low, possible rounding off may be observed) [15]

Final likely structure: austenite + massive carbide + some dispersed carbide or austenite + massive carbide

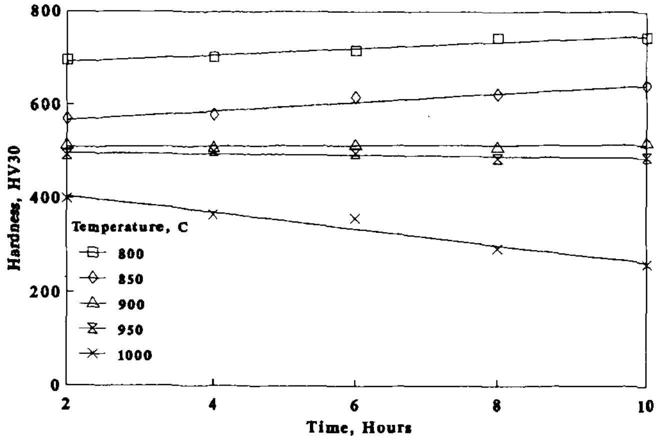

Fig. 1 Variation in hardness with time at different temperatures.

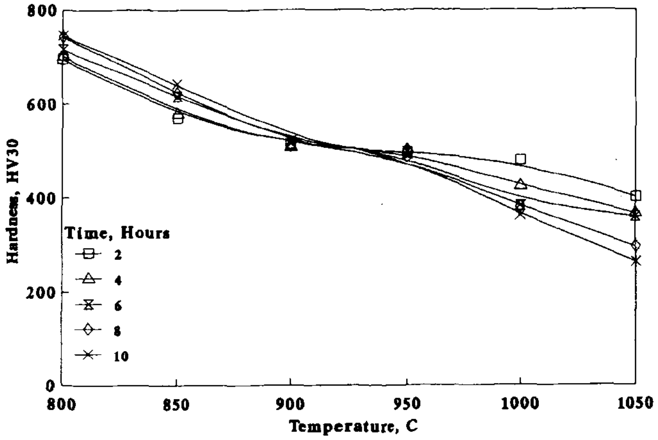

Fig. 2 Variation in hardness with temperature at different times.

In the light of above microstructural changes, the variation in hardness on heat treating (Table 2 and Fig. 1 and 2) can be explained as follows.

The high hardness (652 HV30) in the as-cast condition (Table 2) is consistent with the microstructure observed consisting of pearlite/bainite + martensite + massive carbide + retained austenite (?) (Eq 1 to 3).

At 800 °C, high hardness (Fig. 1) after 2 h of soaking is due to the formation of a martensitic matrix (Eq 5). Hardness increased marginally with time (Fig. 1) due to the formation of some dispersed carbides at longer soaking times (Eq 4).

On heat treating at 850 °C, the lower hardness at 2 h of soaking (Fig. 1) is due to the retention of austenite (Eq 6). The increase in the hardness with soaking time (Fig. 1) is due to the formation of martensite and to the formation of a larger volume fraction of dispersed carbides, as per Eq 4 and 5. The lower overall hardness attained on heat treating at 850 °C, compared to that observed on heat treating from 800 °C (Fig. 2), is due to an increase in the austenite stabilizing tendency and hence to the formation of a relatively smaller volume fraction of martensite.

On heat treating at 900 °C, the lower hardness (Fig. 1) at 2/4 h soaking is due to a further increase in the austenite stabilizing tendency (Eq 9). Increasing the soaking time has practically no effect on the hardness because the microstructure is basically unaltered except for limited coarsening of the dispersed carbides (Eq 11) and some reduction in the volume fraction of the massive carbides (Eq 12). The lower overall hardness at 900 °C compared to that observed on heat treating from 850 °C (Fig. 2) is largely due to an increase in the amount of retained austenite. This effect is marked at the longest soaking time.

The basic structural changes on heat treating at 950 °C are similar to those occurring on heat treating at 900 °C, except that the coarsening of dispersed carbides is enhanced and the reduction in the volume fraction of massive carbides is larger. These changes, which promote the retention of a relatively larger volume fraction of stable austenite, not only result in a lower overall hardness compared to that observed on heat treating from 900 °C, but are also responsible for a slight decrease in hardness with soaking time (Fig. 1). The volume fraction of massive carbides has decreased to a level so as to contribute to the decreasing hardness trend.

On heat treating at 1000 °C, the lower hardness at 2 h soaking is due to (1) a predominantly austenitic matrix rendered even more stable (Eq 13) and (2) a further decrease in the amount of massive and dispersed carbides (Eq 14 and 15). The decrease in hardness with soaking time (Fig. 1) is due to a marked decrease in the volume fraction of massive carbides and to a near complete dissolution of the dispersed carbides.

Structural changes on heat treating at 1050 °C are similar to those observed at 1000 °C, but are still further accelerated as the temperature is higher. This leads to a decrease in hardness with soaking time (Fig. 1). This decrease would have been steeper but for the formation of an austenite + carbide eutectic (perhaps with a high hardness) whose formation was initiated at 1000 °C and which has now resolved itself into an eutectic-like morphology. Its volume fraction initially increased with soaking time (4 to 6 h) and decreased thereafter on increasing the soaking time to 10 h. The lowest overall hardness at 1050 °C is due to the presence of a predominantly high stability austenitic matrix containing very small amounts of massive carbide and the eutectic.

The above analysis further makes it clear that the hardness would vary linearly with time at different heat treating temperatures. However, for a given heat treating period, the decrease in hardness with temperature would be steep, up to 900 °C, very gradual up to 950 °C, and once again steep thereafter on increasing the temperature up to 1050 °C, *i.e.*, would occur nonlinearly.

3.1.4 *Development of an Interrelation Between Hardness and Heat Treating Parameters*

From the discussion presented earlier, it can be concluded that hardness varies linearly with soaking time and, therefore, can be represented as $H + C1 + C2.t$

The values of $C1$ and $C2$ were found to be different for different temperatures and, therefore, can be expressed as:

$C1 = f(T)$ and $C2 = f(T)$

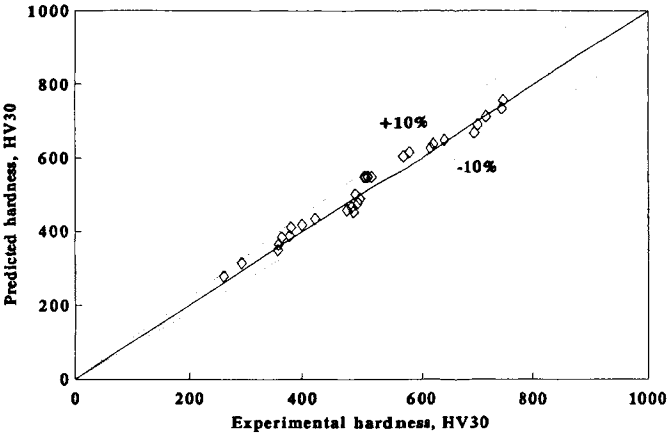

Fig. 3 Iso-hardness plot showing predicted hardness well within ±10% of experimental hardness.

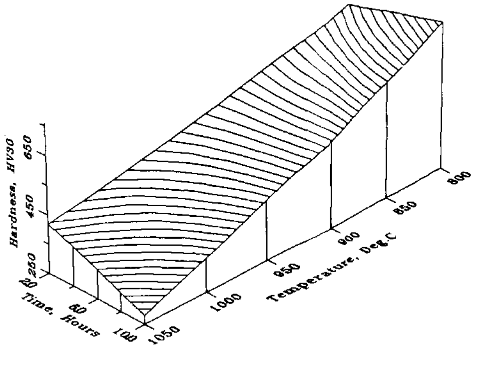

Fig. 4 Three-dimensional plot representing the variation in hardness with *h*/*t* parameters.

The plots of $C1$ versus T and $C2$ versus T revealed that $C2$ versus T is linear and yields the relationship $C2 = A3 + A4.T$. However, the $C1$ versus T plot was exponential in nature. A plot between ln $C1$ versus $1/T$ indicated linear behavior, and hence, the relation between $C1$ and T can be expressed as:

$$\ln C1 = A1 + A2.1/T \text{ or } C1 = A1.e^{A2/T}$$

Substituting for $C1$ and $C2$ in the initial equation, the final relationship is:

$$H = A1.e^{A2/T} + (A3 + A4.T)t$$

The constants $A1$, $A2$, $A3$, and $A4$ were determined using a [illegible] nonlinear constraint optimization technique.[illegible] [illegible]

$$H = 98.285e^{2021.33/T} + (0.037 - 0.316 \times 10^{-4}T) \cdot t$$

where H is hardness (HV30); T is soaking temperature (K); and t is soaking time (seconds).

The theoretical hardness values calculated from the above equations were plotted against the corresponding experimental values (Fig. 3). Most of the predicted values are well within ±10% of the experimental values.

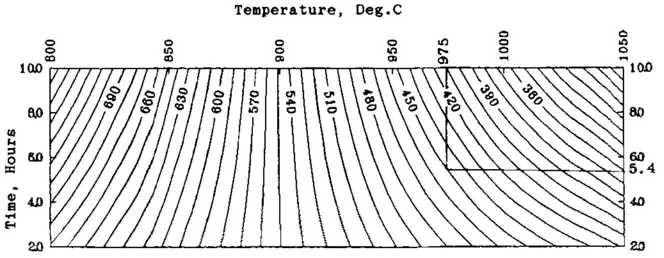

Fig. 5 Iso-hardness plot representing contours of constant hardness.

3.2 *Preparation of Iso-hardness Plot*

The effect of soaking temperature and time on hardness is shown in Fig. 1 and 2. Although these plots can be used to understand the effect of one heat treating parameter (*e.g.*, soaking temperature or time) on hardness, while maintaining other parameters constant, it is not easy to use this technique to predict the optimum parameters to obtain the desired hardness unless the effects of both heat treating parameters on hardness is represented simultaneously. This can be achieved by making a three-dimensional plot of hardness and the two heat treating parameters. Hardness values obtained based on the above derived interrelation

$$H = 98.285e^{2021.33/T} + (0.037 - 0.316 \times 10^{-4}) \cdot t$$

by varying temperature, T, in the range 800 to 1050 °C and time, t, from 2 to 10 h at an interval of 50 °C and 2 h, respectively, were used to make the three-dimensional plot (Fig. 4).

This plot revealed that the variation in hardness with temperature and time can be shown by a surface instead of lines, as in Fig. 1 and 2. The surface consisted of lines of constant hardness. It further revealed that this plot can be used beneficially to understand the transformation behavior of the alloy under study. However, it is still somewhat difficult to optimize the heat treating parameters to achieve a desired hardness. Selection of these parameters can be simplified by projecting the surface of the three-dimensional plot on the temperature-time plane, thus creating an iso-hardness plot, as shown in Fig. 5.

3.3 *Prediction of Heat Treating Parameters to Obtain Desired Hardness*

To predict the heat treating parameters needed to achieve a desired hardness (*e.g.*, 450 HV30), a contour line of the desired hardness value is selected first. With the help of this line, the range of the temperature (952 and 1010 °C) as well as time (2 and 10 h) can be obtained by intersecting the temperature and time axes with the contour line. This limits the range of temperature and time in which the desired hardness can be achieved. A suitable temperature within the above specified range (*e.g.*, 975 °C) is first selected, and the soaking time is obtained by drawing a line from the cross point of the hardness contour and the selected temperature to the time axis. The line intersects the time axis at 5.4 h. Therefore, to achieve 450 Vickers hardness at 975 °C, the soaking time should be 5.4 h.

4. Conclusions

Hardness varied linearly with soaking time, whereas the variation was nonlinear with soaking temperature. It can be represented as:

$$H = 98.285e^{2021.33/T} + (0.037 - 0.316 \times 10^{-4}T)\,t$$

The effect of heat treating parameters on hardness can be best represented and explained by a three-dimensional plot between hardness, soaking temperature, and soaking time.

The iso-hardness plot can be prepared by projecting the surface comprised of constant hardness lines in a three-dimensional plot on the temperature-time plane. The iso-hardness plot can be used extensively to predict heat treating parameters to achieve the desired hardness in an alloy system upon heat treating.

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