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The tempering parameter for evaluating softening of hot and warm forging die steels

E. Virtanen[a], C.J. Van Tyne[a,*], B.S. Levy[b], G. Brada[c]

[a] Department of Metallurgical and Materials Engineering, Colorado School of Mines, Golden, CO 80401, USA
[b] B.S. Levy Consultants Ltd., 1700 E. 56th St., Suite 3705, Chicago, IL 60637, USA
[c] A. Finkl & Sons, Co., 2011 N. Southport Ave., Chicago, IL 60614, USA

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ABSTRACT

The tempering characteristics of three different hot and warm forging die steels (FX, 2714, and WF) were systematically studied over a range of temperatures (316–677 °C) and a range of times (1–300 h). The softening rate for each steel was determined by the change in room temperature hardness. In this study, the hardness data are quantitatively related to the tempering parameter via regression analysis. The tempering parameter (also known as the Hollomon–Jaffe parameter or the Larson–Miller parameter) accounts for the effects of both tempering time and tempering temperature. Room temperature hardness is a measure of the microstructural change that occurs during the tempering process. Results from this study show a bilinear softening as a function of the tempering parameter. For hot and warm forging application the second portion of the curve is more applicable, since these die steels are tempered to some extent before initial use. The slope of the curve can be used as a measure of softening, which is one of the contributing factors on how well the die steel will perform in actual forging operations. These results indicate that WF has the highest resistance to softening during use, FX is somewhat less resistance to softening, and 2714 is the least resistant of the three die steels studied.

1. Introduction

Tempering is a low temperature heat treatment given to martensitic steels usually after the steel has been quenched. Tempering improves the toughness of the steel but causes a decrease in the hardness. Tempering is performed on forging die steels before they are initially put into service so that they will have the prerequisite toughness to meet the demands of the process. During production of hot or warm forgings the dies are subjected to heating usually of short duration by contact with the workpiece. This subsequent heating of the die steels can cause further tempering to occur especially in the surface layer of the die.

The tempering parameter, also known as the Hollomon–Jaffe (1945) parameter or the Larson–Miller (1952) parameter, combines the effect of time and temperature to describe the change in hardness during tempering of steels. The kinetics of the solid state reactions, which control the decrease in hardness depends primarily on the diffusion of carbon or nitrogen in the steel. The tempering parameter has been used for a number of industrial operations that depend upon both time and temperature. Such operations include the strain aging or paint bake aging of steels and the tempering of martensite. Gomes et al. (2010) have used the tempering parameter to predict the mechanical properties of quenched and tempered carbon steel. Janjusevic et al. (2009) have examined a high strength low alloy steel using the tempering parameter.

The present study evaluates the tempering parameter for steels with higher alloy content than in previous studies and at longer times and higher temperatures than are typically used for tempering martensite. The resulting data are applicable for evaluating the performance and softening resistance of hot or warm forging die steels during use. With greater resistance to softening the die steel can be used for longer production runs.

Shivpuri et al. (2005) indicate that adhesive wear, which is the primary cause for loss of dimensional control in hot forged parts, is a major factor that limits die life. Adhesive wear depends on the softening of the extreme outer surface layers of the hot forging die. The surfaces of the impressions in hot or warm forging dies are softened by repeated contact with hot workpieces. The tempering parameter can be used to quantify the surface softening, which is one of the contributing factors in wear of dies during production.

Various studies have been conducted in examining hot forging die life based on a die tempering analysis. Kang et al. (1998) have used the tempering parameter in a wear model to predict the useful die life of hot and warm forging tools. The die steel that they investigated was H13. Kang et al. (1999a) developed a wear model for

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[*] Corresponding author. Tel.: +1 303 273 3793; fax: +1 303 273 3016.
E-mail addresses: evirtanen@mines.edu (E. Virtanen), cvantyne@mines.edu (C.J. Van Tyne), bslevycons@ameritech.net (B.S. Levy), guyb@finkl.com (G. Brada).

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Table 1
Nominal compositions of the forging die steels.

Steel	C	Mn	Si	Ni	Cr	Mo	V
FX	0.50	0.85	0.25	0.90	1.15	0.50	
2714	0.55	0.85	0.25	1.65	1.15	0.50	0.10
WF	0.42	0.75	0.50	0.80	2.50	1.00	0.08

hot forging dies which incorporates the tempering parameter. They developed a four parameter empirical fit of the tempered hardness for various dies as a function of the tempering parameter. The fitted equation exhibited a curvilinear behavior consistent with their experimental data. Kang et al. (1999b) used their wear model, based on the tempering parameter to compare with actual wear profiles in forging dies. They found very good agreement between their model and the experimental results. Kim et al. (2005) also used the tempering parameter in developing a model for the useful service life of H13. The limitations for the use of H13 were a combination of wear and local plastic deformation and the resistance of dies to both mechanisms decreased with increased values of the tempering parameter. Choi et al. (2012) examined the die wear and plastic deformation limits of warm forging dies with the use of the tempering parameter. They integrated their model into a finite element analysis of the process. They found that plastic deformation in addition to wear on the surface of the die caused limitations of die life. Zhao et al. (2011) used the tempering time and tempering temperature as two separate variables to study and improve the die life for hot forging of a steel gear ring. They observed that more wear was seen after forging for longer times or at higher temperatures.

Tempering of steel can be studied by metallographic observation or by hardness measurements. Since metallographic observation is time consuming compared to measuring hardness, hardness is normally used as a measure of the amount of tempering. In evaluating the hardness results, it must be recognized that the reported hardness values do not represent strength of the die steel at forging temperatures. The hardness measurements are used as a generalized metric to quantify the microstructural changes that occur due to tempering as the hot or warm forging production progresses. The change in microstructure at the extreme surface of the die controls both local die wear and local yield strength which leads to loss of dimensional control in forged parts.

The billets for hot steel forging are normally heated to 1100–1200 °C, and the forging dies are usually preheated to 200–300 °C. When the hot workpiece comes in contact with the forging dies, the surface of the die is heated to high temperatures for relatively short periods of time. In this study, die heating in the range from 316 to 677 °C is investigated by use of the tempering parameter. Three commonly used hot forging die steels, FX, 2714, and WF, were held for times ranging from 1 to 300 h over the temperature range of the study. Since the tempering parameter is a proven method for determining the combined effect of time and temperature on tempering of steel, the room temperature hardness of these die steels is assessed as a function of the tempering parameter. The objective of the study is to determine the behavior of the three die steels as a function of times and temperatures consistent with a steel forging process and to make a comparison between the expected performance of the three die steels.

2. Experimental procedures

2.1. Materials

This investigation examined three die steels – FX, 2714, and WF. Table 1 shows the nominal compositions for these three steels. The initial materials were received in the form of as-quenched rectangular blocks with dimensions of 50.8 mm by 44.5 mm by 12.7 mm.

Table 2
Hardness of as-received forging die steels.

Steel	Hardness (HV)	Uncertainty[a] (HV)	Hardness (HRC)	Uncertainty[a] (HRC)
FX	753	±18.2	61.5	±0.9
2714	716	±29.1	59.8	±1.3
WF	773	±17.3	62.6	±0.9

[a] One standard deviation.

Table 2 gives the initial hardness of the as-received steels. Each block was sectioned into four specimens before heat treatment. The specimen dimensions were 25.4 mm by 22.2 mm by 12.7 mm.

Table 3 lists the tempering temperatures and times for the three steels. All combinations of temperatures and times were used in the experimental work, resulting in forty-eight tempering conditions for each steel. The specimens were tempered in air using a resistance heated furnace followed by air-cooling. The holding time at temperature started when the furnace returned to the set point temperature after placing the specimen into the furnace. Normally there was about a 20 °C drop in temperature when specimens were placed in the furnace, and it took about 5 min to return to the set point temperature.

2.2. Specimen preparation prior to hardness testing

Prior to heat treatment one side of each sample was ground. After heat treatment, the surface was ground to a fine roughness and followed by polishing with a 6-μm diamond paste suspension. Sample hardness was measured within one hour of polishing.

With longer heating times and higher temperatures, a thin hard layer of reaction products was created on steel surface that was assumed to have formed by oxidation of the steel surface during heating. The thin oxide layer was more difficult to remove by grinding as compared to the surface of the non-heat-treated steel. The thin oxide layer had a negligible effect on sample preperation. For the two highest temperatures, some samples had a thicker scale layer that peeled off when they were being prepared for grinding. The thickest scale, which occurred at the 677 °C temperature for 300 h, was less than 0.2 mm. The effect of the thin oxide layer or the peeled oxide layer as well as any small amount of decarburization was believed to have no significant effect on the results.

2.3. Micro hardness testing

After samples had been heat-treated and polished to a fine surface finish, micro hardness was determined using a Vickers indenter with a 500 g load for 10 s. Micro hardness measurements were used because they can be accurately converted to nano hardness as demonstrated by Mencin et al. (2009). In determining the hardness of the surface layer of a die, the use of nano hardness testing is preferred because it more accurately represents the extreme surface of the die, which is where wear occurs.

Table 3
Tempering temperatures and times.

Temperatures		Times
(°C)	(°F)	(h)
316	600	1
371	700	3
427	800	10
482	900	30
538	1000	100
593	1100	300
649	1200	
677	1250	

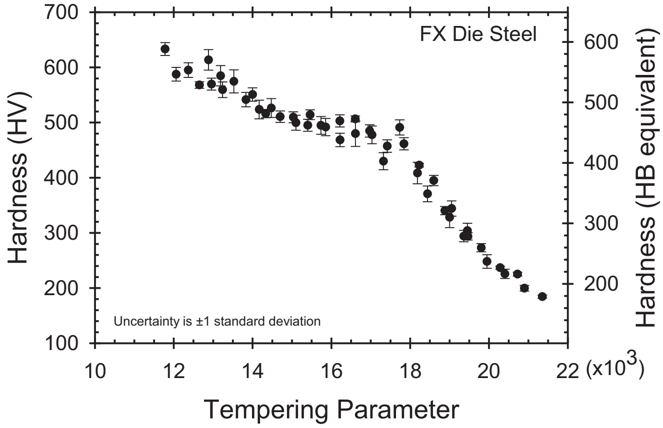

Fig. 1. Hardness of tempered FX as a function of the tempering parameter.

A minimum of six micro hardness measurements per sample was taken, although seven to nine measurements were typical. In a few instances, when higher than normal variation was observed the sample was tested up to thirty times.

Since the tempering parameter is typically used with Rockwell C hardness (HRC), the Vickers hardness (HV) was related to Rockwell C hardness using an equation determined from hardness tables.

$$\mathrm{HRC} = 0.2787 \times 10^{-6}\,\mathrm{HV}^3 - 0.549 \times 10^{-3}\,\mathrm{HV}^2 + 0.4032\,\mathrm{HV} - 49.783 \qquad (1)$$

3. Results

The tempering parameter is used to combine the effect of each heat-treating time and temperature for each hot forging die steel in this study. The tempering parameter, TP, is

$$TP = T \times (C + \log t) \qquad (2)$$

where T is temperature (in K), t is time (in h) and C is a constant. The value of C for time in hours that is reported for tool steels by Roberts et al. (1947) is 20. In graphical presentations the tempering parameter, TP, is normally multiplied by 10^{-3}, since this scaling factor brings the numerical values into a more reasonable range. The values of TP normally range from about 12,000 to 25,000 and the scaling factor reduces the range to 12–25.

Figs. 1–3 show plots of Vickers's hardness versus the tempering parameter for the three steels in the study. The Vickers scale is essentially linear with respect the Brinell hardness so that the secondary ordinate provides the equivalent Brinell hardness number. The uncertainty values are one standard deviation of the multiple hardness tests performed for each condition. It can be seen that the data points in Figs. 1–3 exhibit a curvilinear relationship. However, when the hardness values are converted to the Rockwell C scale using Eq. (1), the relationship between the hardness and the tempering parameter becomes bilinear.

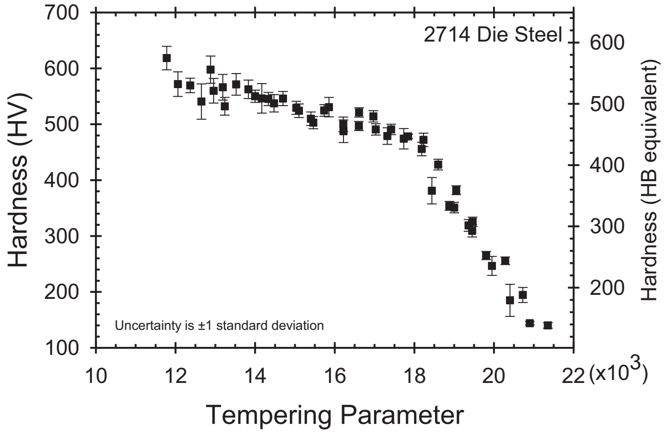

Fig. 2. Hardness of tempered 2714 as a function of the tempering parameter.

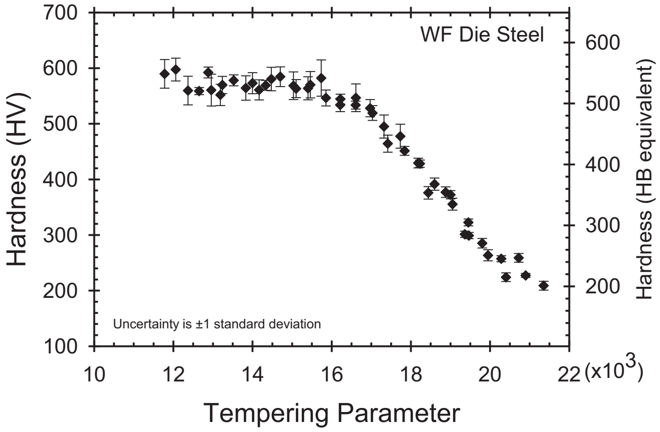

Fig. 3. Hardness of tempered WF as a function of the tempering parameter.

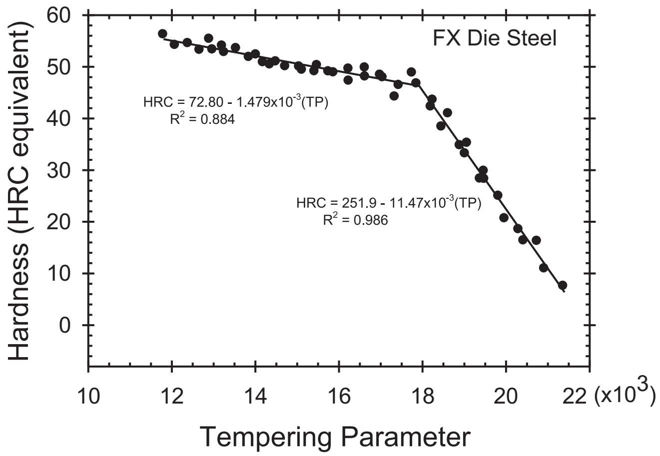

Fig. 4. Hardness of tempered FX in Rockwell C equivalent with regression lines.

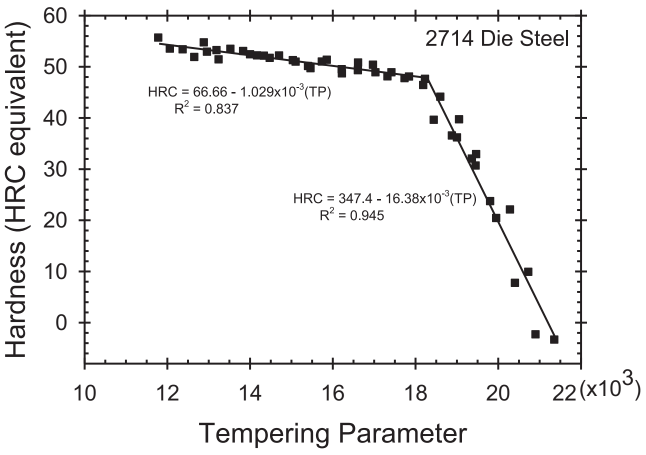

Fig. 5. Hardness of tempered 2714 in Rockwell C equivalent with regression lines.

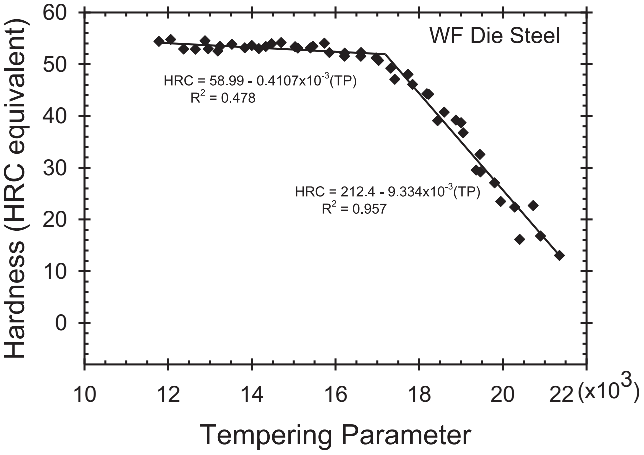

Fig. 6. Hardness of tempered WF in Rockwell C equivalent with regression lines.

Figs. 4–6 show plots of HRC hardness versus the tempering parameter for steels FX, 2714 and WF respectively. In Figs. 4–6, there are two distinct linear regions for each of the three steels in the study. This bilinear behavior of HRC hardness as a function of the tempering parameter is different than the curvilinear decrease observed by Kang et al. (1999a) for H13. Upon closer examination of the data by Kang et al. (1999a) there is a significant lack of data points between tempering parameter values of 14,500 and 20,000 which is not the case for the present investigation.

Over small ranges of temperatures or small ranges of times, plots of HRC versus the tempering parameter often give a single straight line. The bilinear behavior exhibited by the experimental data provides a usable method to combine the effects of time and temperature into a single variable. It is hypothesized that the two regions of this bilinear behavior represent different stages of the tempering process. Thomas et al. (2010) have shown that the various stages of tempering can give curves with different slopes.

The linear regions for each steel were regressed using the form

$$\mathrm{HRC} = a_0 + a_1 \mathrm{TP} \tag{3}$$

where HRC is the Rockwell C hardness value, TP is the tempering parameter and a_0 and a_1 are the intercept and slope of the regression line respectively. Figs. 4–6 show the regression lines and the square of the correlation coefficient (R^2). It can be seen that the lines in Figs. 4–6 are a reasonable representation of the data. It can also be seen that R^2 is function of the slopes of the regression line. For regression lines with a shallow slope, smaller R^2 values are observed. Small R^2 values for nearly flat lines are an artifact of regression statistics, because the regression line differs only slightly from the average of the data set. Since the regression for nearly constant data explains little of the variation in data points compared to the average value, the value of R^2 is low. Thus, even regression lines with low R^2 values can be reasonable representations of the data.

The intersection of the two lines for each steel was determined by solving the two regression equations for the common point. Figs. 4–6 include these intersection points. These transitions points have HRC values of 46.3, 47.8 and 51.9 respectively for FX, 2714 and WF.

Fig. 7 provides a direct comparison of the tempering behavior of the three steels. The transition point for WF occurs at the smallest value of the tempering parameter but the slope of the second linear region is the least. In contrast 2714 has the highest value for the tempering parameter at the transition point but the steepest slope for the second linear region. The behavior of FX is between the other two die steels.

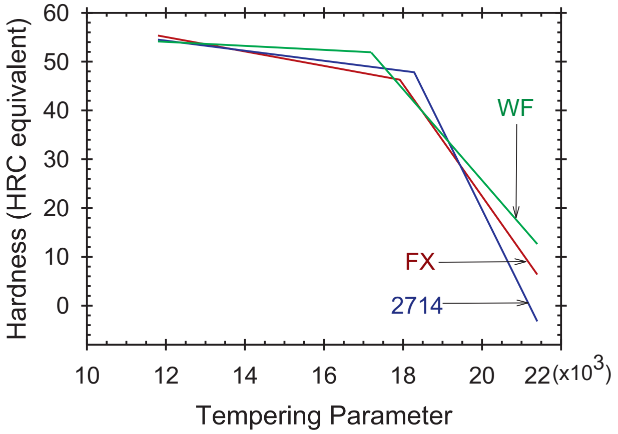

Fig. 7. Comparison of the tempering behavior of all three die steels in the study.

Table 2 gives the as-received hardness for the three steels. It can be seen from Figs. 4–6 that the hardness at the lowest value of the tempering parameter, which is about 12,000 for the heat treating experiments in this study, is substantially less than the as-received hardness for all three steels. Using the regression results, the value of the tempering parameter that equals the as-received hardness can be calculated. These results are for FX, 2714, and WF respectively are 7600, 6700, and −8700. For FX and 2714, it can be seen that there is no tempering for values of the tempering parameter less than 7600 and 6700 respectively. For WF, the negative value of the tempering parameter suggests that tempering starts at shorter times and lower temperatures, but progresses at a very slow rate.

4. Discussion

4.1. Effect of time and temperature

The tempering parameter combines the effect of time and temperature on tempering behavior. For practical applications, it is useful to consider the effect of time and temperature separately. Hardness versus the tempering parameter exhibits a bilinear relationship for the three die steels in this study. The regression equations can be used to show the change in hardness as a function of time at temperatures of 450, 500, 550 and 600 °C. In calculating hardness for the bilinear curves shown in Figs. 4–6, the initial regression equation is used until the value of the tempering parameter reaches the value for the intersection of the two lines. Thereafter, the second regression equation is used in the calculations. For temperatures for which there is a transition between the two lines, the slope of the hardness versus time curve shows a slope discontinuity.

Figs. 8–10 show the relation between Rockwell C hardness and time for respectively FX, 2714, and WF at temperatures of 450, 500 550, and 600 °C. It can be observed that at 450 °C for all three steels, time has a minimal effect on hardness. At 500 °C, FX and 2714 still exhibit minimal decreases in hardness with time, but WF decreases as a result of the lower value of the tempering parameter at the transition between the two straight lines. At 550 and 600 °C, all three steels exhibit a rapid decrease in hardness with time.

4.2. Resistance to softening

Typical die steels for hot forging applications are tempered to about 40 HRC before initial use. The value of 40 HRC is below the transition point for all three steels; so the second line can used to compare the behavior of die steels in forging operations. The die steels in this study can be compared by examining the softening

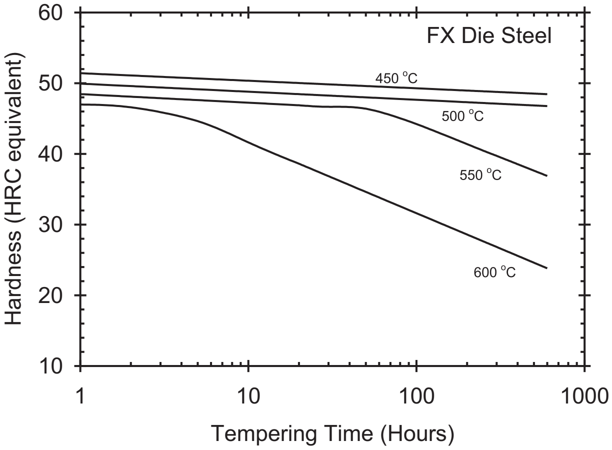

Fig. 8. Effect of tempering time on Rockwell C hardness for tempering temperatures of 450, 500, 550, and 600 °C for FX.

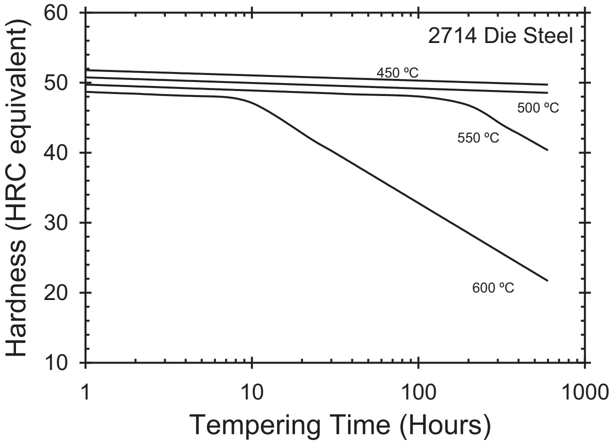

Fig. 9. Effect of tempering time on Rockwell C hardness for tempering temperatures of 450, 500, 550, and 600 °C for 2714.

rate. The softening rate is the first derivative of Eq. (3) with respect to TP.

$$\frac{d(\mathrm{HRC})}{d(\mathrm{TP})} = a_1 \tag{4}$$

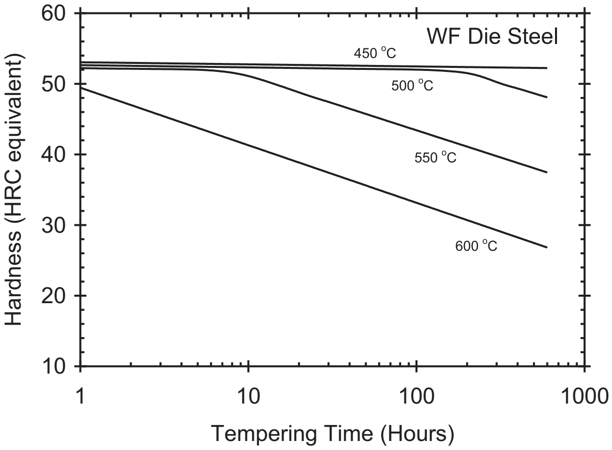

Fig. 10. Effect of tempering time on Rockwell C hardness for tempering temperatures of 450, 500, 550, and 600 °C for WF.

The use of the slope of the tempering parameter curve provides a very efficient method to compare various die steels with respect to their performance in hot forging operations. The higher the softening rate the shorter the production run that can be expected when using the die steel for hot forging. A higher softening rate will have a steeper slope in the second region (i.e. a more negative value for a_1).

The softening rate for FX, 2714, and WF is coefficient, a_1, for the second line. These softening rates are -11.5×10^{-3}, -16.4×10^{-3}, and -9.3×10^{-3} for FX, 2714 and WF, respectively. Thus in practical operations, WF has the most resistance to softening, FX has a somewhat less resistance to softening, and 2714 has the least resistance to softening during forging. This ranking is not too surprising since WF has much high alloy content as compared to FX and 2714. With the additional molybdenum and chromium in WF more alloy carbides can form during tempering and thus provide greater softening resistance when used in hot forging processes. The compositions of FX and 2714 are fairly similar with 2714 having additional nickel. The extra nickel in 2714 contributes to increased toughness but seems to have a slightly deleterious effect on the softening behavior when used at higher temperatures.

5. Summary

1. Hardness is used to characterize the effect of tempering, and the effect of time and temperature are analyzed separately to show their individual effects on the softening rate of die steels. Hardness is a measure of the microstructural changes during the tempering process.
2. This study has shown that the tempering parameter can be used to characterize the softening response of hot forging die steels. The slope of the tempering parameter curve in the range used in production can be used to efficiently compare the softening behavior of various die steels. To illustrate this comparison method, WF shows the highest resistance to softening during use, FX is somewhat less resistance to softening, and 2714 has the most softening during forging for the three die steels studied. This ranking is based on the slope to the tempering parameter curve in the region of HRC 40 or less which is the type hardness range for forging dies when they are initially put into service.

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