Tempering Behavior of Hot Forging Die Steels

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Abstract

Experimental data of the hardness of three die steels (FX, 2714 and WF) were measured as a function of tempering time and temperature. The temperatures ranged from 316 °C (600 °F) to 677 °C (1250 °F) and the times ranged from 1 hour to 300 hours. The data are presented in the form of a plot of hardness as a function of the Larsen-Miller parameter. The Larsen-Miller parameter is a standard variable that accounts for both the time and temperature experienced by a tempered steel. All three steels showed a bilinear behavior when the hardness in Rockwell C was plotted versus the Larson-Miller parameter. Linear regressions were calculated for both linear regions in each of the three steels. A plot of these linear regression lines allowed the three steels to be compared to one another. The FX was found to have the most softening in the low temperature-short time region, whereas the 2714 had the most softening at the high temperature-long time region. The WF performed the best of the three steels with respect to temper resistance. The WF die steel had an almost constant hardness in the low temperature-short time region and exhibited the least amount of softening in the high temperature-long time regime.

1. Introduction

Die wear is a major cause of failure for hot forging dies. Failure is caused by a rapid increase in wear that causes the forging impression to grow beyond specified tolerances, which effectively terminates the useful die life. Understanding die wear requires improved understanding of changes that take place in the surface layer of hot forging dies during use. The following conditions cause changes to the microstructure and properties of the die steel surface layer during forging: 1) time at high temperatures due to contact with the hot workpiece, 2) shear stresses associated with metal flow and friction, and 3) contact pressure, where contact pressure depends on the properties of the work material, part shape, and die design.

Die wear depends on the strength of the surface layer of the die steel at forging temperatures. It is possible that the wear is the result of over-tempering of the surface layer of die steels. If the decrease in strength at temperature is related to over-tempering of the surface layer of a forging die, this effect can be observed at room temperature by either metallographic analysis or hardness testing. Detailed metallographic observation of tempered martensite is too expensive to be practical, but changes in hardness can be used to evaluate tempering.

Macro and micro hardness measurements are thought to be too coarse to effectively determine the strength of the surface layer of a hot forging die. Nano hardness testing, because of its small indentation, may provide a method to study the changes that occur to the surface layer. An initial project in evaluating wear in hot forging dies via hardness testing of the surface layer examined the relationships between nano hardness, micro hardness, and macro hardness using samples with uniform properties so that the different hardness tests evaluate the same microstructure [1]. The results of this initial study showed that the values measured by nano hardness, micro hardness, and macro hardness tests provide comparable results.

The purpose of the present project was to develop experimental data of the hardness of die steels as a function of tempering time and temperature. Tempering curves (i.e. plots of hardness as a function of the Larsen-Miller parameter) are used to assess the results of the experimental tests. The Larsen-Miller parameter is a variable that accounts for both the time and temperature experience by a piece of metal. These tempering curves can be used in conjunction with nano hardness tests on the surface of dies to provide a better understanding of die wear.

2. Experimental Procedures

2.1 Materials

An FX die steel, a 2714 die steel, and a WF die steel were used in this study. Table 1 shows the nominal compositions for these three steels. Table 2 gives the initial hardness values for the three steels as-received.

The initial materials were received as hardened blocks of dimensions: 50.8 mm x 44.5 mm x 12.7 mm (2.00 in x 1.75 in x 0.50 in). Each block was sectioned into four pieces with an abrasive cut off wheel into four specimens before heat treatment. The specimens were spray cooled with water during the sectioning process. The sectioned specimens were of dimensions: 25.4 mm x 22.2 mm x 12.7 mm (1.00 in x 0.88 in x 0.50 in).

Various tempering heat treatments were given to the three steels. There were eight different temperatures and six different times at each temperature for a total of forty-eight tempering conditions for each steel. Table 3 gives the temperatures and times for these heat treatments. The temperatures varied from 316 ^{o}C (600 ^{o}F) to 677 ^{o}C (1250 ^{o}F). The times varied from 1 to 300 hr. All the specimens were tempered in a Carbolite CWF 1200 furnace in air. 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 ^{o}C (36 ^{o}F) drop in temperature when placing them in the furnace, and it took approximately minutes for the furnace to return to the set point temperature. After tempering the specimens were air cooled.

2.2 Specimen Preparation Prior to Hardness Testing

Initially the heat treated samples were ground manually to fine roughness and then polished with 6 µm diamond paste suspension. After preparing a few samples in this manner, the method for preparing the samples was changed slightly. The reason for the change was to produce a more uniform and finer surface quality on the heat treated samples. In the modified sample preparation one side of the samples was ground before heat treating. This made grinding of the sample easier and to a more uniformed depth after the heat treatment. The polishing of the sample was still done with 6 µm diamond paste suspension. It was observed that finer polishing did not reduce the variation for the hardness values. Although during hardness testing of samples that were polished with 6 µm polish, some scratches were present on the surface of tested material, it was possible to make hardness measurements in areas without scratches. After polishing the hardness of the samples was measured within one hour.

With longer heating times and higher temperatures a thin hard layer of reaction products was created on steel surface. The layer was assumed to have formed by oxidation of steel surface in the furnace. The oxide layer was noticeably more resistant to abrasion of the grinding paper than the base steel. The layer was thin and its effects in the preparation of the sample were minor. For the two highest temperatures some samples had a thicker scale layer that pealed when they were being prepared for grinding. The effect of pealing of the scale was not believed to have affected the results. The thickest scale, which occurred at the 677^{o}C (1250 ^{o}F) temperature for 300 hours, was less than 0.2 mm.

2.3 Micro hardness testing

After samples had been heat treated and polished to fine surface quality the hardness of the samples was tested with Leco MHT Series 200 -microhardness testing machine. Because some of the samples were slightly larger in size than the chamber of the mounting press, the samples were not mounted prior to hardness testing.

In microhardness testing it is important that the tested surface to be flat. If the surface is not flat the diamond-shaped indentation on the sample will not be symmetrical. This asymmetry can cause considerable uncertainty in the hardness value. Obtaining a flat surface was not always easy but it was possible to manually tilt the sample in two directions to get the desired flatness.

In order to test for flatness the microscope was focused in the highest corner of the sample and the other corners were adjusted manually bring the whole sample surface into focus.

The Vickers microhardness tests were performed using a load of 500 g and a dwell time of 10 s. The larger load was used to insure that a sufficient amount of metal was indented making the test more representative of bulk properties.

The number of hardness tests for each sample was at least six. For most samples the number of hardness tests was between seven and nine. In a few instances the variation was observed to be fairly large and the number of tests was increased to thirty. From these measurements the average value and standard deviation of the hardness were calculated.

3. Results

Table 4 gives the hardness data for the tempered FX steel. Table 5 gives the hardness data for the tempered 2714 steel. Table 6 gives the hardness data for the tempered WF steel.

For many grades of steel, time and temperature of tempering are interchangeable. To achieve a given hardness the tempering temperature can be increased but for a shorter time or the temperature can be decreased for a longer time. The relationship between time and temperature for tempering is capture in the Larson-Miller parameter (also called the Holloman-Jaffe parameter or sometimes called the tempering parameter). Empirically it is often found that the hardness after tempering will be constant for constant values of the parameter. The parameter, LM, is

$$LM = T * (C + \log t) \qquad (1)$$

where T is temperature (in K), t is time (in hr) and C is a constant. The value of C that is often reported for low carbon and HSLA steels is 20. If the units of time are given in seconds than the value of C would be 16.45. In this project the units for time are in hours and a value of 20 has been used for the value of C. There are warnings that this approach may not be valid for steels that undergo secondary hardening.

Table 7 lists the Larson-Miller parameters for the various times and temperatures that were used in the project. The low temperatures and short times give low values for the Larson-Miller parameter. In contrast high temperatures and long times give higher values for the parameter.

Figures 1 to 3 show plots of the hardness versus the Larson-Miller parameter for FX, 2714 and WF respectively. In these figures the hardness value is in Vickers (HV), which was the measured quantity. The uncertainty limits that are shown are plus or minus one standard deviation for the number of measurements on each of the steels. The equivalent Brinell hardness (HB) values are provided on the second axis. There is a linear relationship between HV and HB values so the use of the second axis is natural

4. Discussion

Although most steels show a single linear curve for the hardness versus the Larson-Miller parameter, the three die steels in this study all exhibit two distinct regions. The data for these two regions also exhibit some curvature whereas other steels show a linear behavior.

In order to handle this situation the equivalent Rockwell hardness (HRC) was determined from the HV values. The relationship between HRC and HV is nonlinear. Most straight line tempering curves that appear in the literature are plotted with HRC hardness values.

Figures 4 to 6 show the plots of equivalent HRC values versus the Larson-Miller parameter. The uncertainty limits have not been plotted in order to maintain clarity of the graphs. In these figures it is obvious that the three steels show a bi-linear behavior.

Two linear regression lines were determined for each of the three steels. These two lines are shown in Figures 4 to 6. Figure 7 is a comparison of these bilinear tempering lines for the three steels. This figure allows for a direct comparison of the three steels in the study.

It is seen in Figure 7 that the FX has a slightly steeper slope in the first region as compared to 2714 and WF but in the second region 2714 exhibits the most significant decrease in hardness. The WF die steel maintains an almost constant hardness through the first region and its slope in the second region is the least steep of the three steels.

Although the transition point between the two bilinear regions is shown as a sharp knee in the tempering curves, this sharpness is an artifact of the regression analysis that was performed. In reality the transition is smoother, as exhibited by the actual data points shown in Figures 1 to 3.

5. Summary

The tempering behavior of three different die steels – FX, 2714 and WF – were analyzed by measuring hardness as a function of time and temperature. The temperatures ranged from 316 ^{o}C (600 ^{o}F) to 677 ^{o}C (1250 ^{o}F) and the times ranged from 1 hour to 300 hours. The Larson-Miller parameter was used to provide a single variable, which encompasses both temperature and time. It was found that all three steels showed a bilinear behavior when the hardness in Rockwell C was plotted versus the Larson-Miller parameter. Linear regressions were calculated for both linear regions for each of the three steels. A plot of these linear regression lines allowed the three steels to be compared to one another. The FX was found to have the most softening in the low temperature-short time region, whereas the 2714 had the most softening at the high temperature-long time region. The WF performed the best of the three steels with respect to temper resistance. The WF die steel had an almost constant hardness in the low temperature-short time region and exhibit the least amount of softening in the high temperature-long time regime.

The data in this study can be useful not only in determining the softening of these die steels during use, but may also be used with a proper wear model to determine the useful life of such steels in production of forgings.

6. Acknowledgements

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7. References

[1] P. Mencin, C.J. Van Tyne, and B.S. Levy, "A Method for Measuring Hardness and Elastic Modulus of the Surface Layer on Hot Forging Dies Using a Nano Indentation", FIERF Finkl Challenge Grant Report, September 2007.

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Table 1 Nominal Compositions of the 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

Table 2 Hardness of As-received Die Steels

Steel	Hardness (HV)	Uncertainty* (HV)
FX	753	±18.2
2714	716	±29.1
WF	773	±17.3

* One standard deviation

Table 3 Tempering Temperatures and Times

Temperatures	
(°C)	(°F)
316	600
371	700
427	800
482	900
538	1000
593	1100
649	1200
677	1250

Times
(hr)
1
3
10
30
100
300

Table 4 Hardness Values for the FX Steel

Temperature (^oC)	Time (hr)	Hardness (HV)	Uncertainty (HV)	Sample Size
316	1	633.3	± 11.7	6
316	3	587.5	± 12.4	7
316	10	595.1	± 13.3	14
316	30	568.1	± 5.9	6
316	100	569.6	± 10.8	6
316	300	559.4	± 14.2	6
371	1	613.6	± 18.6	6
371	3	584.8	± 18.5	7
371	10	574.6	± 20.9	7
371	30	541.5	± 13.0	7
371	100	523.6	± 16.9	14
371	300	526.3	± 17.2	16
427	1	550.8	± 12.2	6
427	3	516.2	± 7.5	6
427	10	510.6	± 10.4	6
427	30	509.6	± 9.9	10
427	100	495.0	± 10.8	6
427	300	494.8	± 16.0	10
482	1	499.7	± 13.5	7
482	3	514.2	± 8.8	6
482	10	491.8	± 15.7	6
482	30	502.9	± 10.9	7
482	100	479.9	± 23.3	15
482	300	484.9	± 11.3	6
538	1	468.5	± 12.1	21
538	3	506.5	± 5.4	7
538	10	477.7	± 16.0	7
538	30	457.4	± 11.2	7
538	100	461.5	± 11.0	7
538	300	422.8	± 3.4	7

Table 4 Hardness Values for the FX Steel (continued)

Temperature (^oC)	Time (hr)	Hardness (HV)	Uncertainty (HV)	Sample Size
593	1	429.9	± 15.5	7
593	3	491.2	± 13.7	7
593	10	408.5	± 19.5	7
593	30	395.0	± 9.3	7
593	100	344.1	± 13.8	7
593	300	293.7	± 6.6	7
649	1	370.7	± 14.3	7
649	3	340.3	± 7.5	7
649	10	294.2	± 10.4	7
649	30	273.1	± 7.4	7
649	100	236.9	± 2.9	7
649	300	225.2	± 3.5	7
677	1	328.3	± 18.7	15
677	3	304.1	± 13.3	7
677	10	248.1	± 12.2	7
677	30	225.7	± 8.4	7
677	100	199.6	± 5.2	7
677	300	184.5	± 2.9	7

Table 5 Hardness Values for the 2714 Steel

Temperature (^oC)	Time (hr)	Hardness (HV)	Uncertainty (HV)	Sample Size
316	1	618.4	± 21.0	6
316	3	571.8	± 22.1	7
316	10	569.4	± 12.9	7
316	30	540.6	± 31.6	15
316	100	559.9	± 22.0	21
316	300	532.2	± 15.8	6
371	1	597.7	± 24.4	14
371	3	566.2	± 23.0	7
371	10	571.3	± 19.3	14
371	30	562.5	± 16.5	13
371	100	546.3	± 26.5	14
371	300	537.5	± 15.5	7
427	1	550.1	± 11.0	14
427	3	545.2	± 11.7	14
427	10	546.0	± 12.6	13
427	30	529.3	± 11.6	7
427	100	509.9	± 12.1	6
427	300	524.6	± 10.3	7
482	1	524.2	± 12.2	14
482	3	502.9	± 10.9	7
482	10	530.6	± 17.4	7
482	30	499.8	± 13.2	10
482	100	521.2	± 8.3	14
482	300	514.1	± 10.1	7
538	1	487.5	± 20.3	14
538	3	496.9	± 8.1	8
538	10	490.7	± 10.1	7
538	30	490.7	± 9.3	7
538	100	478.3	± 3.9	7
538	300	472.0	± 12.0	7

Table 5 Hardness Values for the 2714 Steel (continued)

Temperature (^{o}C)	Time (hr)	Hardness (HV)	Uncertainty (HV)	Sample Size
593	1	478.9	± 14.9	7
593	3	474.1	± 18.3	7
593	10	455.7	± 12.2	7
593	30	427.9	± 9.6	7
593	100	382.0	± 7.9	7
593	300	325.4	± 8.3	7
649	1	381.0	± 23.7	21
649	3	354.0	± 7.9	7
649	10	319.0	± 10.4	7
649	30	265.1	± 7.3	7
649	100	255.7	± 6.8	7
649	300	194.5	± 13.4	7
677	1	350.9	± 9.4	7
677	3	309.3	± 10.9	7
677	10	246.4	± 17.0	7
677	30	184.9	± 28.7	24
677	100	143.9	± 3.0	7
677	300	140.0	± 5.0	7

Table 6 Hardness Values for the WF Steel

Temperature (^oC)	Time (hr)	Hardness (HV)	Uncertainty (HV)	Sample Size
316	1	589.7	± 25.8	12
316	3	597.5	± 20.5	18
316	10	559.7	± 25.7	27
316	30	558.8	± 6.4	6
316	100	560.6	± 28.7	6
316	300	569.8	± 15.4	13
371	1	592.3	± 9.8	6
371	3	552.0	± 19.1	13
371	10	578.1	± 9.8	6
371	30	564.3	± 21.9	6
371	100	561.0	± 18.1	6
371	300	580.4	± 21.1	21
427	1	573.0	± 18.9	14
427	3	569.1	± 9.0	14
427	10	584.6	± 17.8	9
427	30	568.5	± 24.8	19
427	100	563.8	± 20.7	10
427	300	582.2	± 32.7	30
482	1	563.2	± 16.2	19
482	3	570.2	± 23.7	13
482	10	546.4	± 14.3	13
482	30	533.8	± 11.9	12
482	100	546.7	± 24.9	22
482	300	528.0	± 15.5	19
538	1	544.4	± 8.8	7
538	3	533.6	± 7.2	7
538	10	519.3	± 13.3	8
538	30	464.3	± 15.3	8
538	100	451.3	± 8.0	7
538	300	428.3	± 6.5	7

Table 6 Hardness Values for the WF Steel (continued)

Temperature (^oC)	Time (hr)	Hardness (HV)	Uncertainty (HV)	Sample Size
593	1	495.0	± 20.8	7
593	3	477.6	± 21.5	7
593	10	429.4	± 8.7	7
593	30	391.5	± 11.0	7
593	100	355.4	± 10.7	7
593	300	299.0	± 5.5	7
649	1	375.9	± 11.3	14
649	3	377.0	± 9.5	7
649	10	301.4	± 5.7	14
649	30	285.2	± 8.6	7
649	100	257.3	± 5.5	7
649	300	258.9	± 7.8	7
677	1	372.4	± 7.5	7
677	3	322.6	± 6.1	7
677	10	263.5	± 10.0	7
677	30	224.1	± 7.8	7
677	100	227.3	± 3.6	7
677	300	208.9	± 7.9	7

Table 7 Larson-Miller Parameter Values

Temperature (^{o}C)	Time (hr)	Larson-Miller Parameter ($\times 10^{-3}$)
316	1	11.78
316	3	12.06
316	10	12.37
316	30	12.65
316	100	12.96
316	300	13.24
371	1	12.88
371	3	13.19
371	10	13.52
371	30	13.83
371	100	14.17
371	300	14.48
427	1	14.00
427	3	14.33
427	10	14.70
427	30	15.03
427	100	15.40
427	300	15.73
482	1	15.10
482	3	15.46
482	10	15.86
482	30	16.22
482	100	16.61
482	300	16.97
538	1	16.22
538	3	16.61
538	10	17.03
538	30	17.42
538	100	17.84
538	300	18.23

Table 7 Larson-Miller Parameter Values (continued)

Temperature (^{o}C)	Time (hr)	Larson-Miller Parameter ($\times 10^{-3}$)
593	1	17.32
593	3	17.73
593	10	18.19
593	30	18.60
593	100	19.05
593	300	19.47
649	1	18.44
649	3	18.88
649	10	19.36
649	30	19.80
649	100	20.28
649	300	20.72
677	1	19.00
677	3	19.45
677	10	19.95
677	30	20.40
677	100	20.90
677	300	21.35

Note: C = 20 for the Larson-Miller parameter calculation.

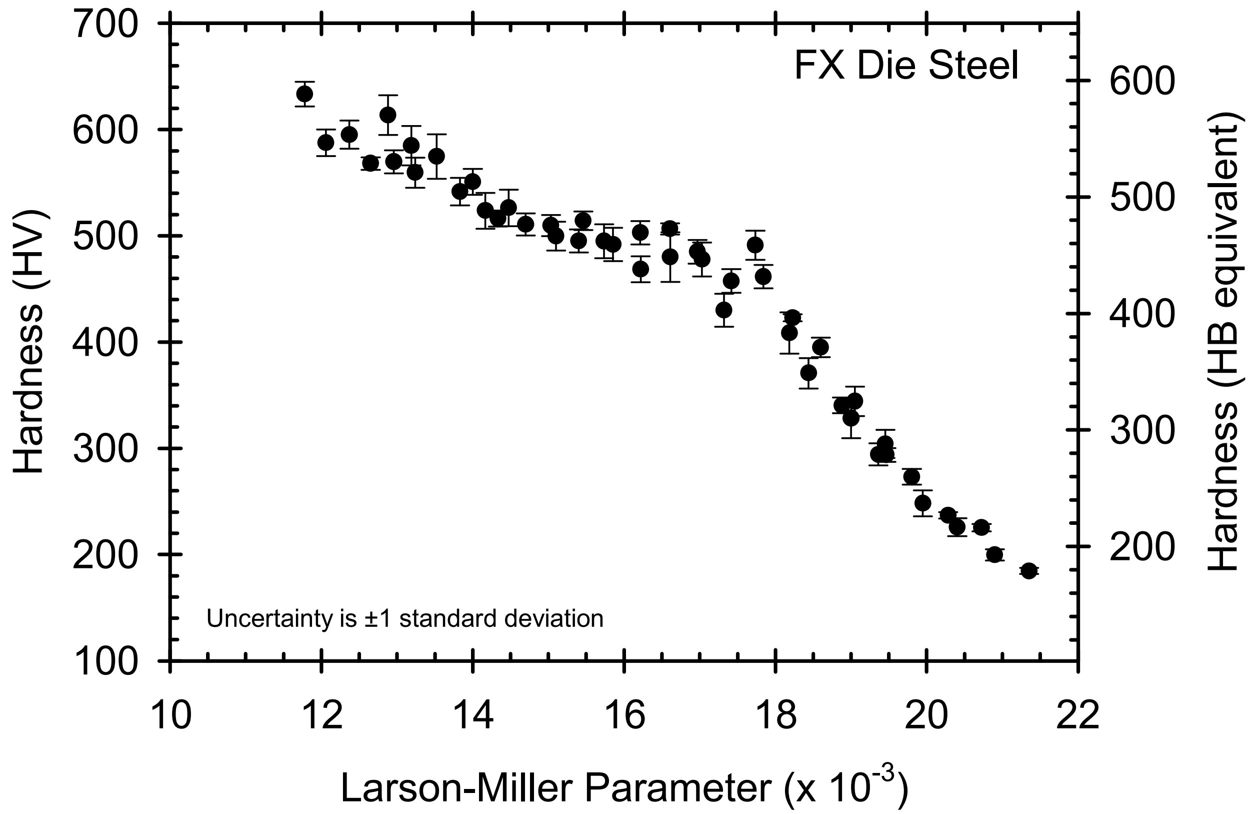

Figure 1 Hardness of tempered FX as a function of the Larson-Miller parameter.

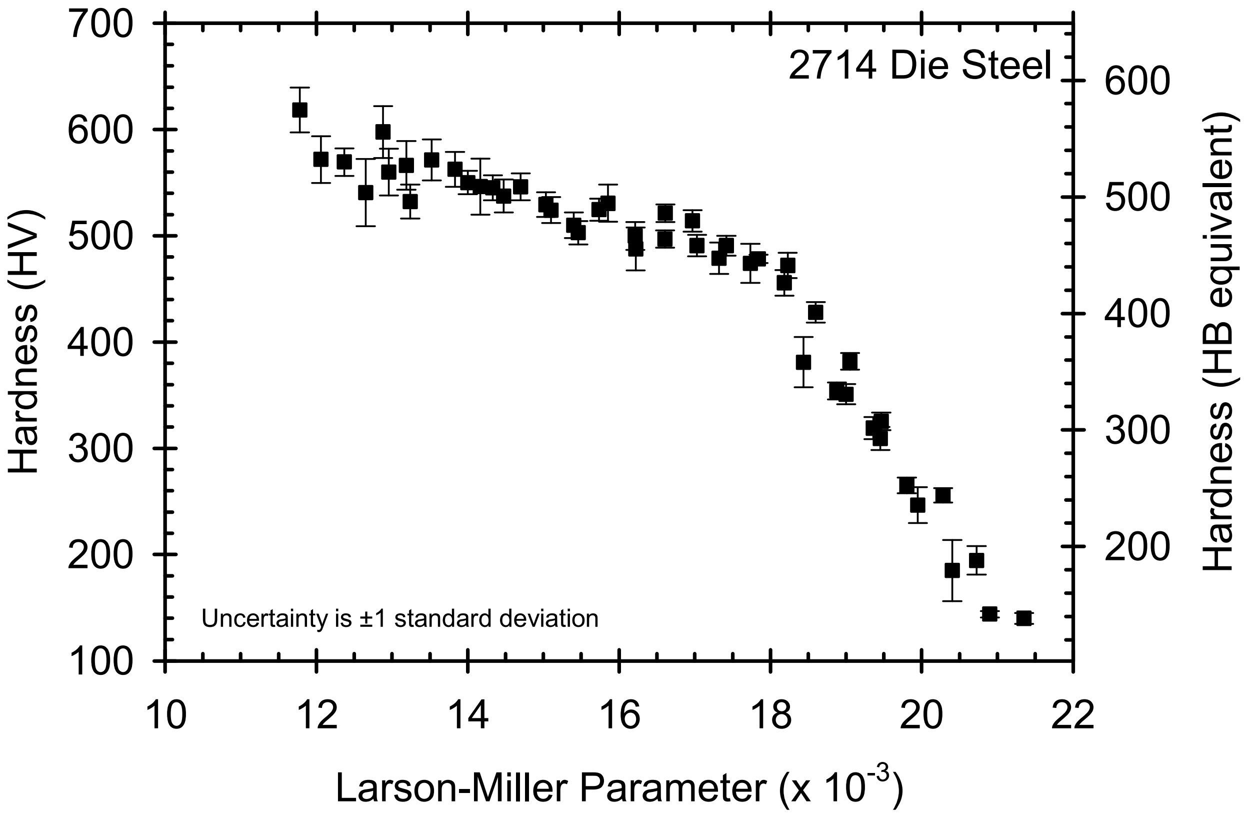

Figure 2 Hardness of tempered 2714 as a function of the Larson-Miller parameter.

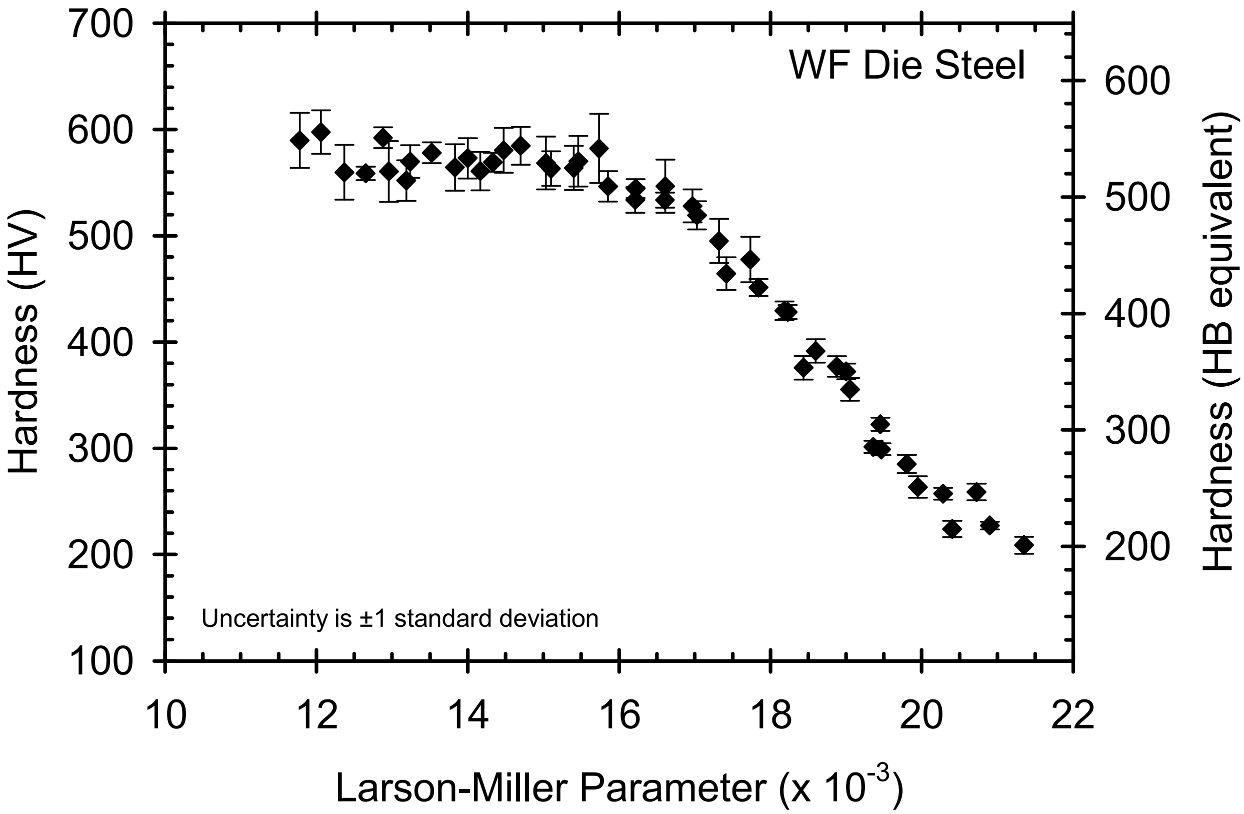

Figure 3 Hardness of tempered WF as a function of the Larson-Miller parameter.

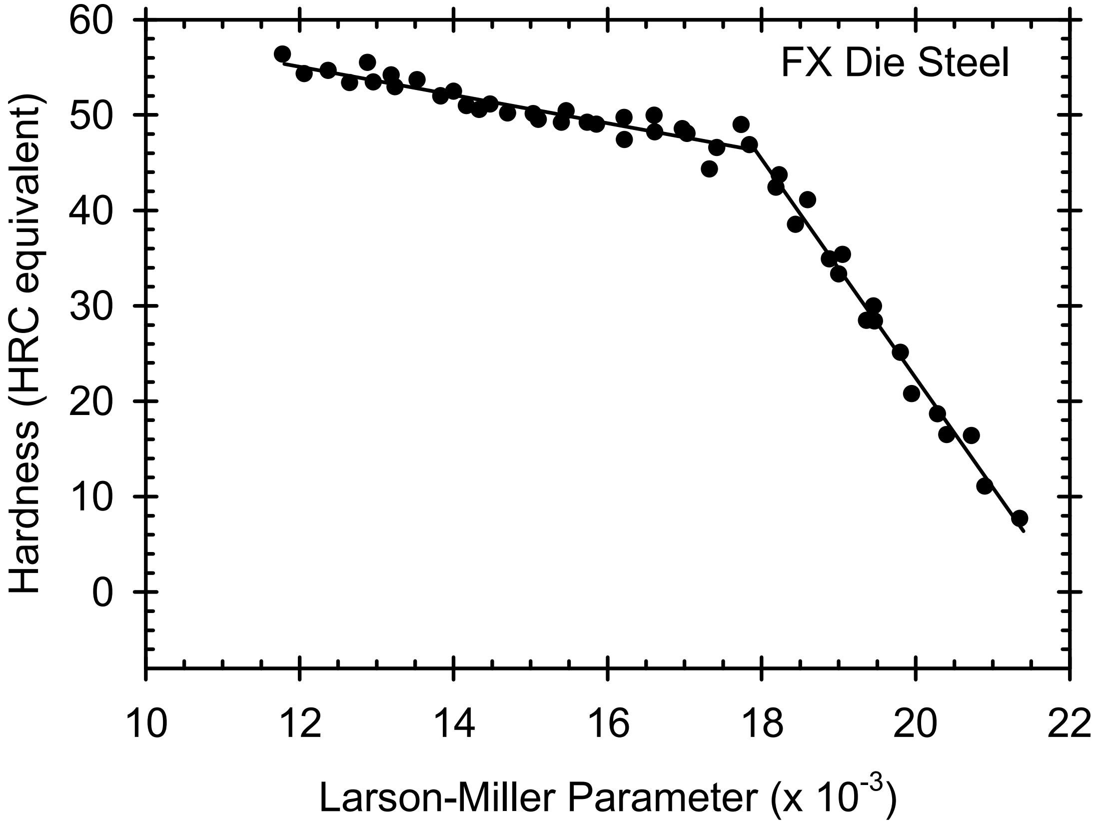

Figure 4 Hardness of tempered FX in Rockwell C equivalent with regression lines.

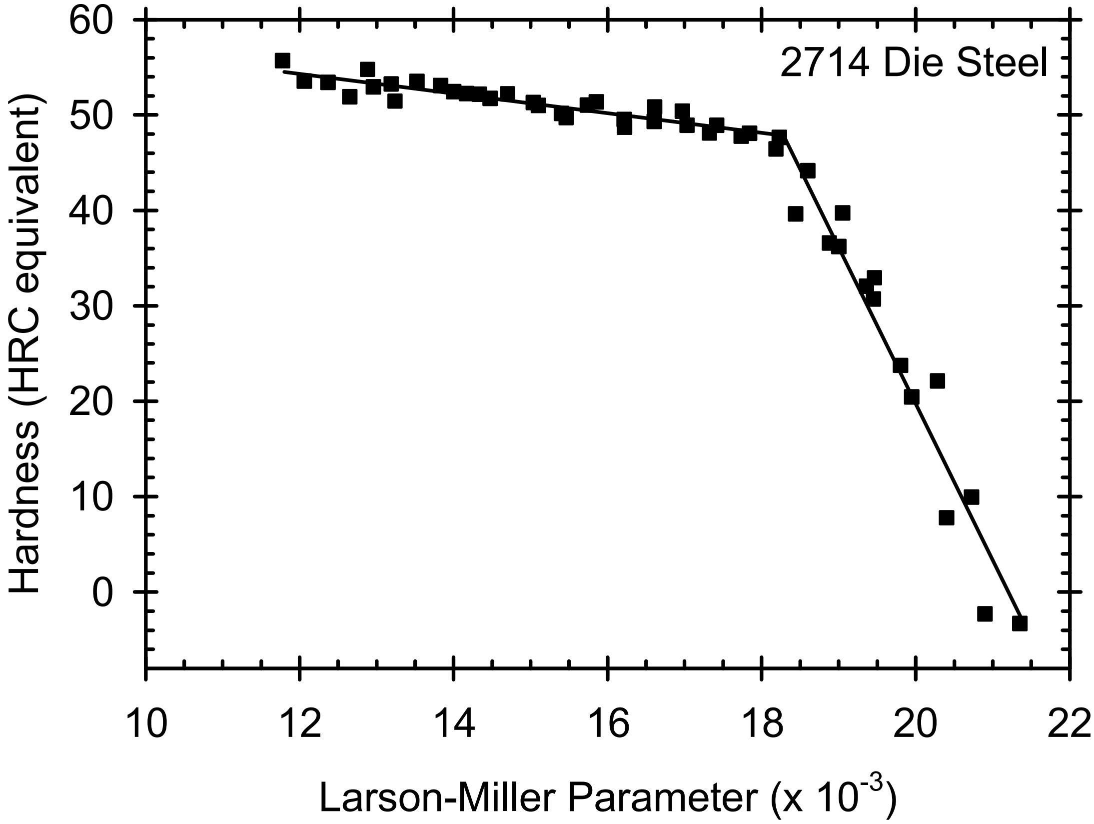

Figure 5 Hardness of tempered 2714 in Rockwell C equivalent with regression lines.

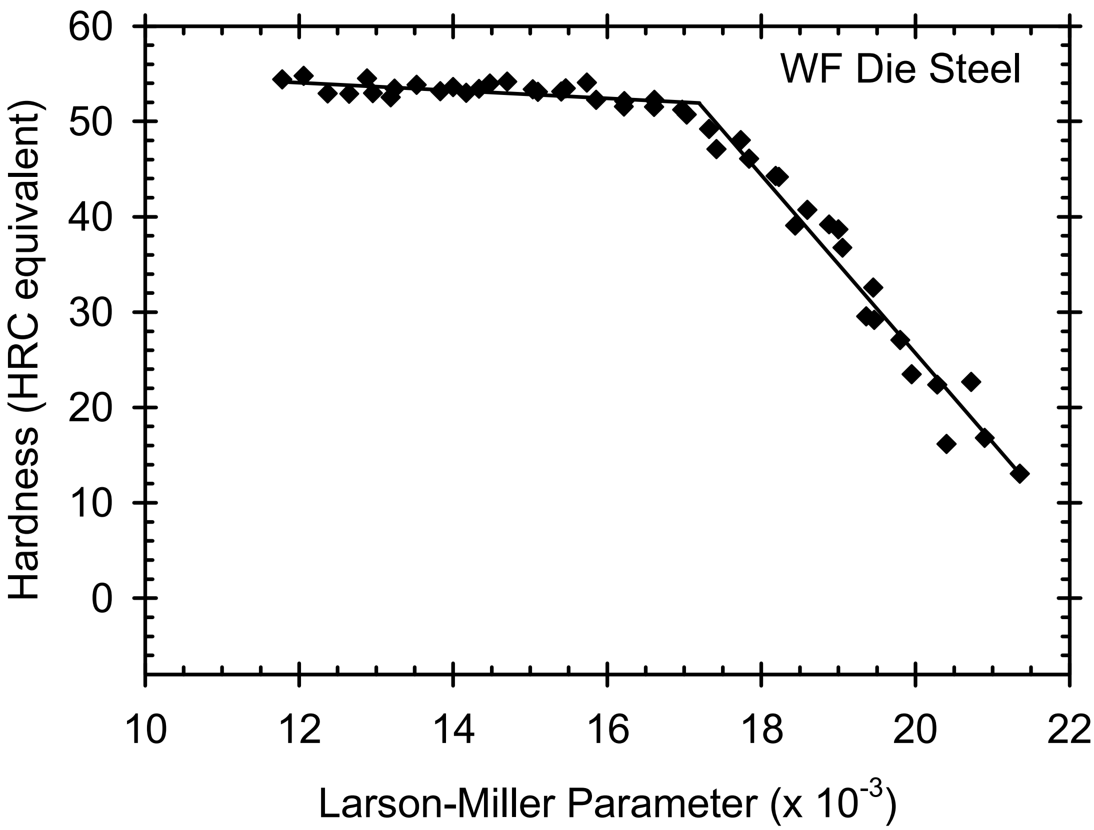

Figure 6 Hardness of tempered WF in Rockwell C equivalent with regression lines.

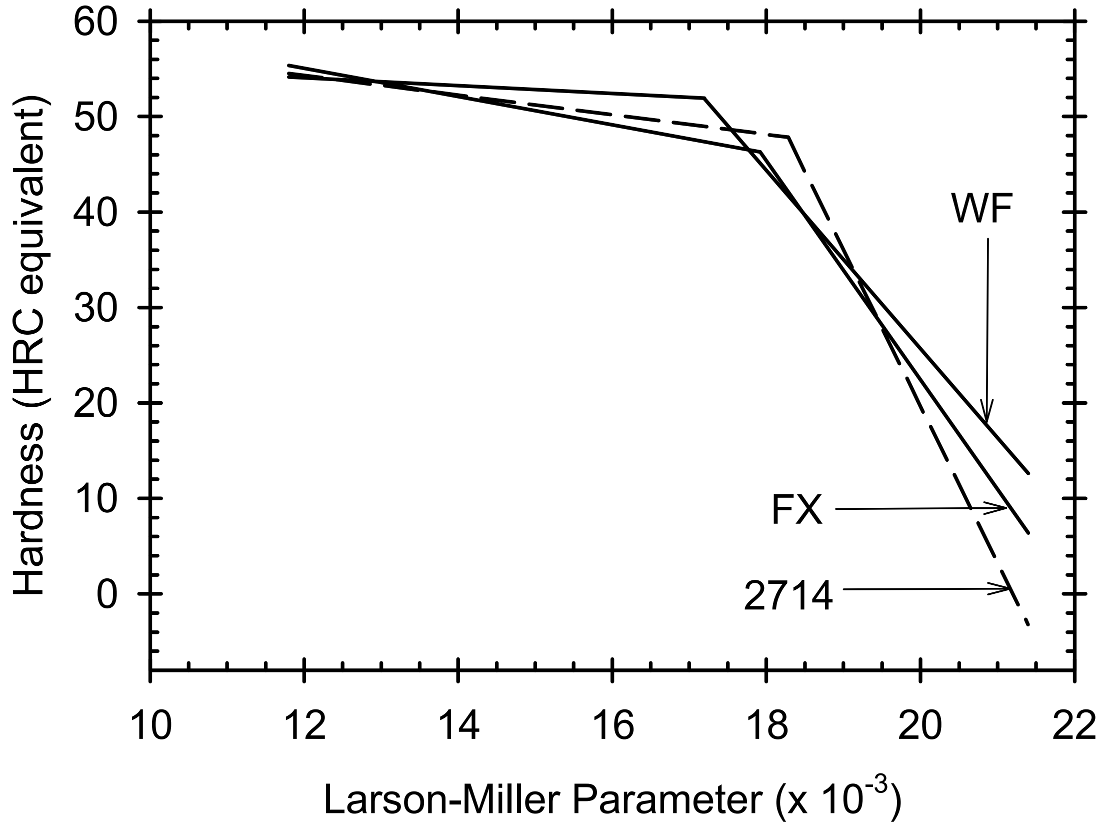

Figure 7 Comparison of tempering behavior for the three die steels – FX, 2714 and WF.