Mechanical Properties of Hot Forging Die Steels at Working Temperatures

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Abstract

Experimental compressive yield strengths were determine for three die steels (FX, 2714 and WF). The die steels were tempered to various hardness values prior to compression testing. The tempered hardness values ranged from 20 to 38 HRC. The temperatures for compression testing ranged from 593 to 704 ^{o}C (1100 to 1300 ^{o}F). It was found that the WF steel which had the highest alloy content was the strongest of the three steels under all test conditions. The FX and 2714, which had similar alloy contents (with FX having slightly less carbon, nickel and vanadium), had yield strengths that were close to each other at the intermediate temperatures, but at the high and low end of the testing range for temperature the FX was stronger than the 2714. Hence, to obtain the greatest resistance to localized plastic deformation during operations the choice of die steel should be WF, followed by FX and then 2714.

1. Introduction

In numerous discussions, forging industry personnel have identified die wear as a major problem that requires further study. Solving the die wear problem requires an increased understanding of the working surface layer of dies. In two past grants [1,2] we have established: 1) a clear relationship between a nano hardness value and a traditional macro or micro hardness value, and 2) the tempering behavior of hot forging die steels using the Larsen-Miller parameter. The relationship between nano hardness and macro hardness allows surface properties to be determined in regions of high wear. The use of the Larsen-Miller parameter allows the combination of time and temperature in a single value that is used to characterize the softening of the hot forging die steel during use. A necessary extension of these two previous projects is to relate the room temperature hardness that was measured during the tempering study to the actual mechanical properties of the hot forging die steel at working temperatures.

The purpose of this project is to produce experimental data of the yield strength behavior of several die steels as a function of temperature after they had been tempered to various hardness levels.

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 as-received three steels.

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). These blocks were sectioned to produce 25 sample blocks for each steel with dimensions 50.8 mm x 19.1 mm x 12.7 mm (2.00 in x 0.75 in x 0.50 in). The steel sample blocks were tempered at various times and temperatures to produce different starting hardness values. The values for the Larsen-Miller parameter [2] were used for each of the steels to obtain the desired hardness. Table 3 gives the experimental hardness values of the three steels after the tempering but prior to the hot compression tests. From each sample block three cylindrical compression test specimens were machined. The dimensions of the compression specimens were 15.0 mm (0.59 in) height x 12 mm (0.47 in) diameter.

2.2 Hot compression testing

Hot compression tests were conducted on the 12 mm diameter cylindrical samples. A hydraulic test frame was used with an attached well insulated clam shell furnace. The platens directly in contact with the sample were made of silicon nitride. Before loading into the test rig, the sample was dipped in Deltaforge 1105 lubricant for 5 s. After the sample was loaded into the clam shell furnace and positioned is the center of the bottom platen, a 15 minute hold occurred to allow the sample to come to temperature. This heat up time was determined using a test sample with thermocouples attached to see how long it took to reach the desired temperature. It is believed that this heat up time had minimal effect on further tempering of the steels.

Compression was applied at the rate of 0.5 mm/s until the sample was reduced from 15 mm to 7.5 mm. The data were acquired digitally at a rate of 100 point per second. Three samples were compressed for most hardness-test temperature conditions. For the three materials, five hardness values and five test temperatures resulted in 225 tests being performed as part of the study. In a few instances only two samples were usable.

2.3 Determination of yield strength

The digital load and displacement data from the compression test were converted to engineering stress - engineering stain data. A plot of engineering stress-engineering strain was used along with a 0.2% offset line to determine the yield strength of the each material. The intersection of the 0.2% offset line, which matched the slope of the stress-strain curve from about 100 to 350 MPa, with the experimental curve was determined to be the yield strength of the material. Figure 1 shows an example of how the yield strength was determined for each test.

3. Results

Table 5 shows the yield strengths for the FX steel. Table 6 shows the yield strengths for the 2714 steel. Table 7 shows the yield strengths for the WF steel.

4. Discussion

Figures 2 to 6 show a comparison of the yield strengths for the three steels at the five test temperatures. A regression analysis was used to determine best fit lines for the entire data set. These regression lines are shown in each figure along with the data values for each steel.

Higher yield strengths at temperature would indicate that the steel is not only stronger but it also implies that the hot hardness is higher. There is a correlation between hardness and wear, with higher hardness materials being more wear resistant. Hence the ranking of these steels with respect to their high temperature strength would also provide a ranking with regard to wear resistance during forging.

From these figures it is observed that in all cases WF is the strongest die steel. Having the highest strength at working temperatures for a range of room temperature hardness values makes it the preferred material for hot die forging. It should be able to withstand the stresses imposed by forging and not degrade as rapidly as the other two steels in the study. The higher alloy content, especially the chromium and molybdenum, gives it the larger high temperature strength.

A comparison of the FX and 2714 steels is also interesting. The results presented in this study show that FX has overall the higher yield strength than 2714. This higher yield strength at high temperatures is present even though FX has less nickel and no vanadium in its nominal composition. Both FX and 2714 have lower alloy content than WF and hence would be expected to be more economical.

The overall ranking of how these three steels would perform during forging is WF first, FX second and 2714 third.

5. Summary

It was found that the WF steel, which had the highest alloy content, was the strongest of the three steels under all test conditions. The FX and 2714, which had similar alloy contents (with FX having slightly less carbon, nickel and vanadium), had yield strengths that were close to each other at the intermediate temperatures, but at the high and low end of the testing range for temperature the FX was stronger than the 2714. Hence, to obtain the greatest resistance to localized plastic deformation during operations the choice of die steel should be WF, followed by FX and then 2714.

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.

[2] E. Virtanen, C.J. Van Tyne, and B.S. Levy, "Tempering Behavior of Hot Forging Die Steels", FIERF Finkl Challenge Grant Report, August 2009.

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Table 1 Nominal Composition 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)	Hardness (HRC)	Uncertainty* (HRC)
FX	753	±18.2	61.8	±0.5
2714	716	±29.1	60.0	±1.4
WF	773	±17.3	62.9	±1.0

* One standard deviation

Table 3 Initial Hardness Values for Steels Prior to Hot Compression Testing

Initial Hardness (HRC)		
FX	2714	WF
23.3 ± 0.5	25.8 ± 1.4	20.0 ± 0.6
25.5 ± 0.7	29.4 ± 0.7	24.5 ± 0.9
28.2 ± 0.5	30.7 ± 0.6	30.7 ± 1.1
32.5 ± 1.2	36.0 ± 1.3	35.3 ± 1.2
36.8 ± 0.8	36.7 ± 0.6	38.4 ± 0.7

Uncertainty is one standard deviation

Table 4 Compression Testing Temperatures

Temperature (^{o}C)	Temperature (^{o}F)
593	1100
621	1150
649	1200
677	1250
704	1300

Table 5 Compressive Yield Strength Values for the FX Steel

Temperature (^{o}C)	Hardness (HRC)	Yield Strength (MPa)
593	23.3	458
593	23.3	462
593	23.3	458
593	25.5	486
593	25.5	492
593	28.2	525
593	28.2	528
593	28.2	526
593	32.5	597
593	32.5	596
593	32.5	598
593	36.8	726
593	36.8	715
593	36.8	706
621	23.3	444
621	25.5	470
621	25.5	464
621	25.5	467
621	28.2	498
621	28.2	488
621	32.5	553
621	32.5	559
621	32.5	562
621	36.8	652
621	36.8	657
621	36.8	653
649	23.3	404
649	23.3	403
649	23.3	405
649	25.5	445
649	25.5	436
649	25.5	432
649	28.2	454

Temperature (^{o}C)	Hardness (HRC)	Yield Strength (MPa)
649	28.2	465
649	28.2	455
649	32.5	506
649	32.5	513
649	32.5	510
649	36.8	607
649	36.8	597
649	36.8	598
677	23.3	375
677	23.3	369
677	23.3	372
677	25.5	393
677	25.5	390
677	25.5	394
677	28.2	401
677	28.2	412
677	28.2	412
677	32.5	446
677	36.8	498
677	36.8	501
677	36.8	497
704	23.3	341
704	23.3	347
704	25.5	352
704	25.5	358
704	25.5	363
704	28.2	384
704	28.2	384
704	32.5	398
704	32.5	402
704	36.8	421
704	36.8	415
704	36.8	422

Table 6 Compressive Yield Strength Values for the 2714 Steel

Temperature (^oC)	Hardness (HRC)	Yield Strength (MPa)
593	25.8	488
593	25.8	502
593	25.8	492
593	29.4	536
593	29.4	540
593	29.4	536
593	30.7	551
593	30.7	550
593	30.7	552
593	36.0	658
593	36.0	663
593	36.7	672
593	36.7	682
621	25.8	473
621	25.8	471
621	25.8	470
621	29.4	500
621	29.4	497
621	29.4	505
621	30.7	520
621	30.7	515
621	30.7	514
621	36.0	644
621	36.0	642
621	36.7	660
649	25.8	446
649	25.8	436
649	25.8	436
649	29.4	464
649	29.4	468
649	29.4	462
649	30.7	485
649	30.7	488
649	30.7	483
649	36.0	544

Temperature (^oC)	Hardness (HRC)	Yield Strength (MPa)
649	36.0	545
649	36.0	540
649	36.7	559
649	36.7	568
649	36.7	565
649	36.7	561
649	36.7	564
677	25.8	393
677	25.8	389
677	25.8	394
677	29.4	416
677	29.4	422
677	29.4	420
677	30.7	429
677	30.7	430
677	30.7	424
677	36.0	506
677	36.0	499
677	36.0	500
704	25.8	338
704	25.8	342
704	25.8	346
704	29.4	358
704	29.4	362
704	29.4	353
704	30.7	366
704	30.7	368
704	30.7	373
704	36.0	400
704	36.0	395
704	36.0	404
704	36.7	398
704	36.7	404
704	36.7	406

Table 7 Compressive Yield Strength Values for the WF Steel

Temperature (^oC)	Hardness (HRC)	Yield Strength (MPa)
593	20.0	427
593	20.0	424
593	20.0	428
593	24.5	488
593	24.5	489
593	24.5	488
593	30.7	608
593	30.7	606
593	35.3	704
593	35.3	696
593	35.3	689
593	38.4	755
593	38.4	753
621	20.0	434
621	20.0	427
621	20.0	419
621	24.5	481
621	24.5	470
621	24.5	463
621	30.7	575
621	30.7	574
621	30.7	569
621	35.3	667
621	35.3	671
621	35.3	677
621	38.4	712
621	38.4	720
621	38.4	710
649	20.0	380
649	20.0	375
649	20.0	382
649	24.5	426
649	24.5	423
649	24.5	426
649	30.7	518

Temperature (^oC)	Hardness (HRC)	Yield Strength (MPa)
649	30.7	512
649	30.7	524
649	35.3	578
649	35.3	583
649	35.3	597
649	38.4	670
649	38.4	668
677	20.0	357
677	20.0	346
677	20.0	345
677	24.5	394
677	24.5	390
677	24.5	396
677	30.7	477
677	30.7	486
677	30.7	484
677	35.3	545
677	35.3	553
677	35.3	548
677	38.4	586
677	38.4	587
677	38.4	577
704	20.0	319
704	20.0	317
704	20.0	321
704	24.5	351
704	24.5	354
704	30.7	417
704	30.7	415
704	30.7	409
704	35.3	472
704	38.4	516
704	38.4	513
704	38.4	514

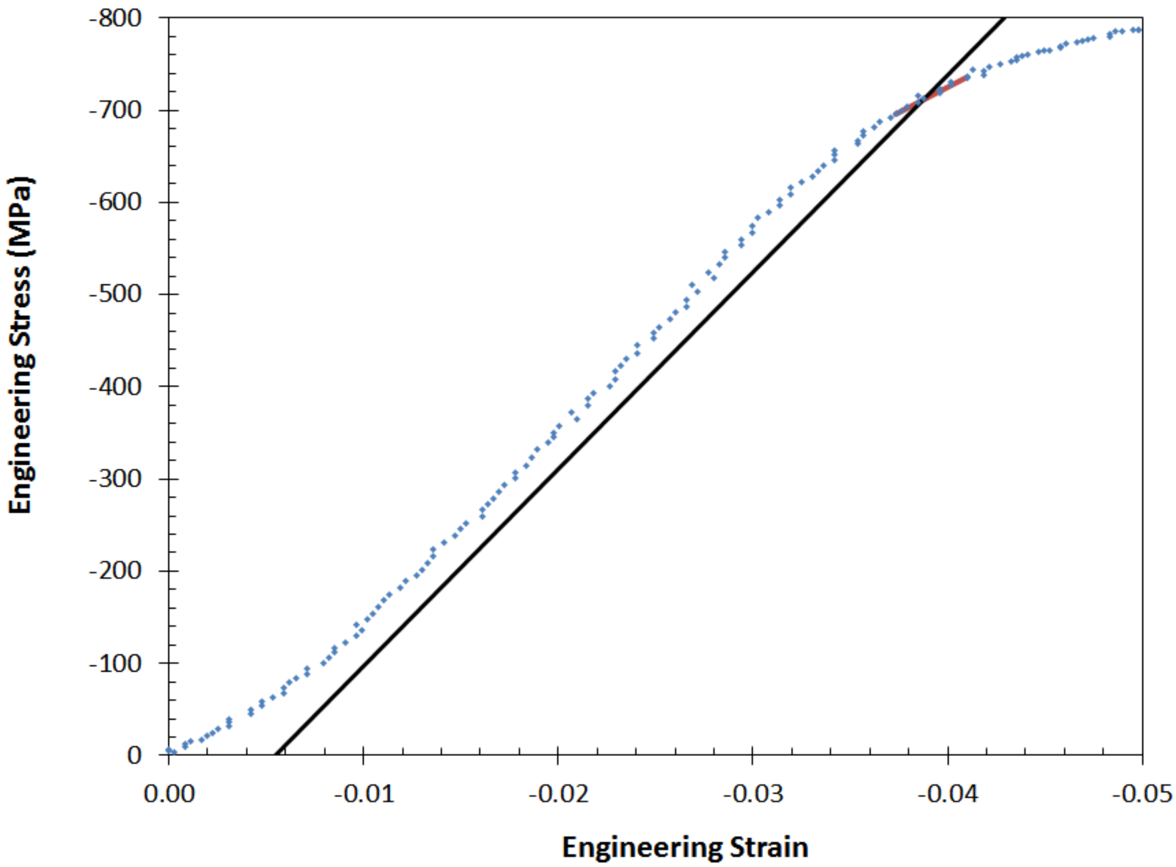

Figure 1 Example of stress-strain curve with 0.2% offset line parallel to the elastic region of the data. Data points are the values determined during the experiment. The intersection of the data points with the 0.2% offset line is the measured yield strength. Data for FX at an initial hardness of 36.8 HRC tested at 593 ^{o}C.

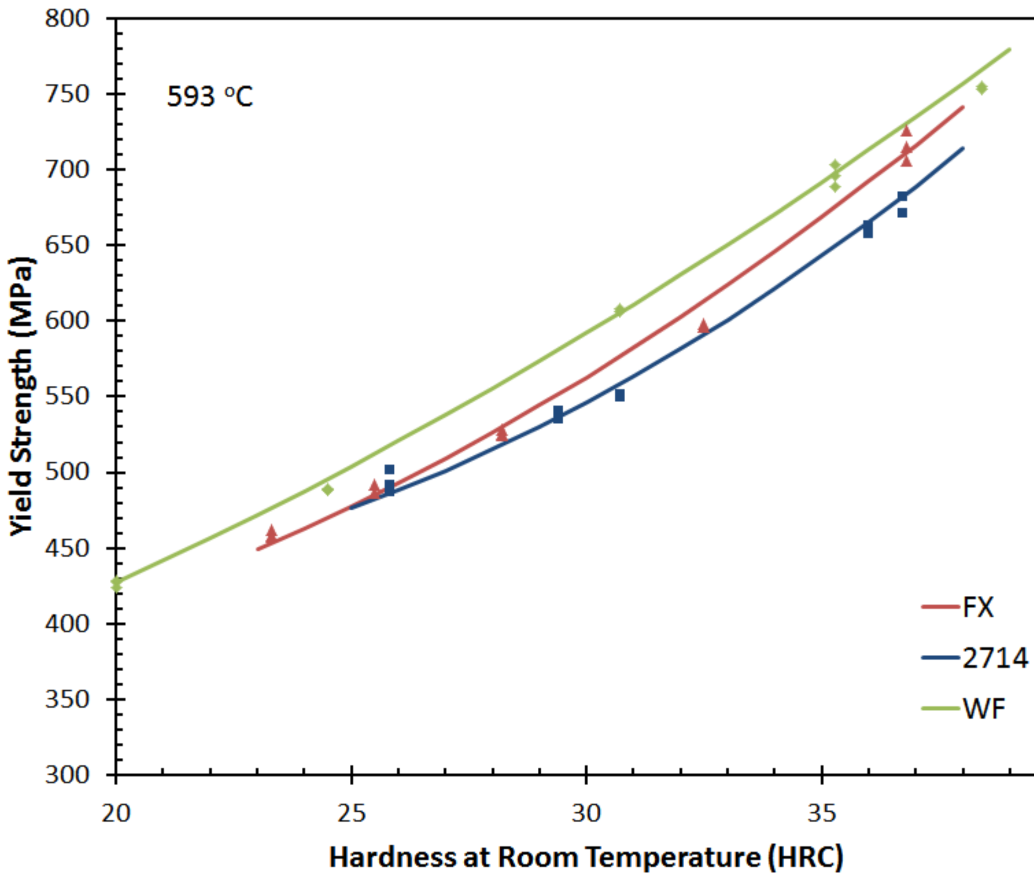

Figure 2 Comparison of yield strengths for the three steels at 593 ^{o}C.

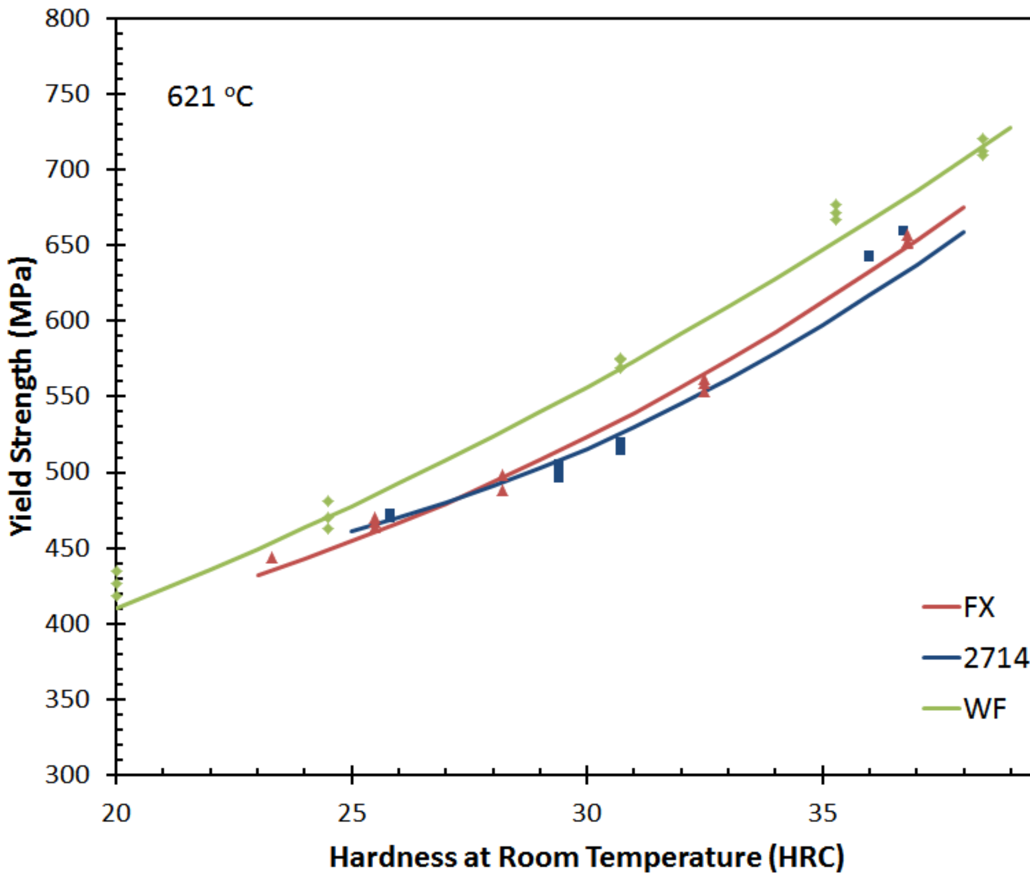

Figure 3 Comparison of yield strengths for the three steels at 621 ^{o}C.

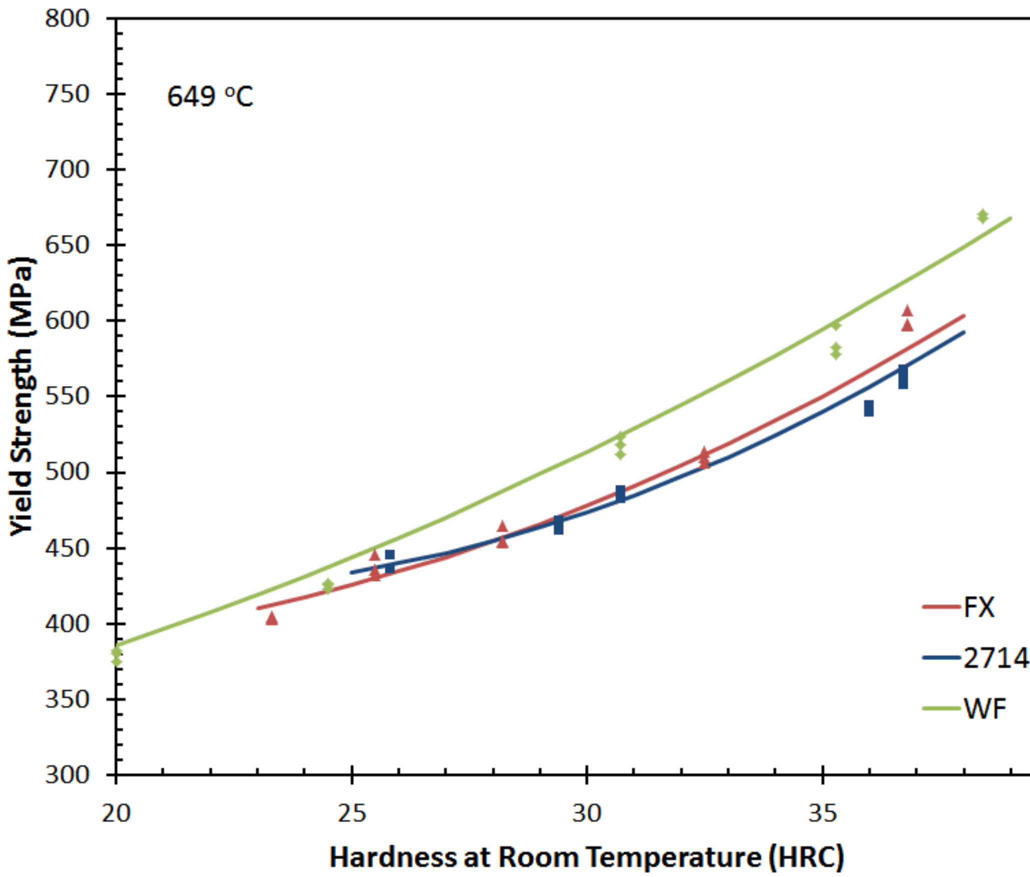

Figure 4 Comparison of yield strengths for the three steels at 649 °C.

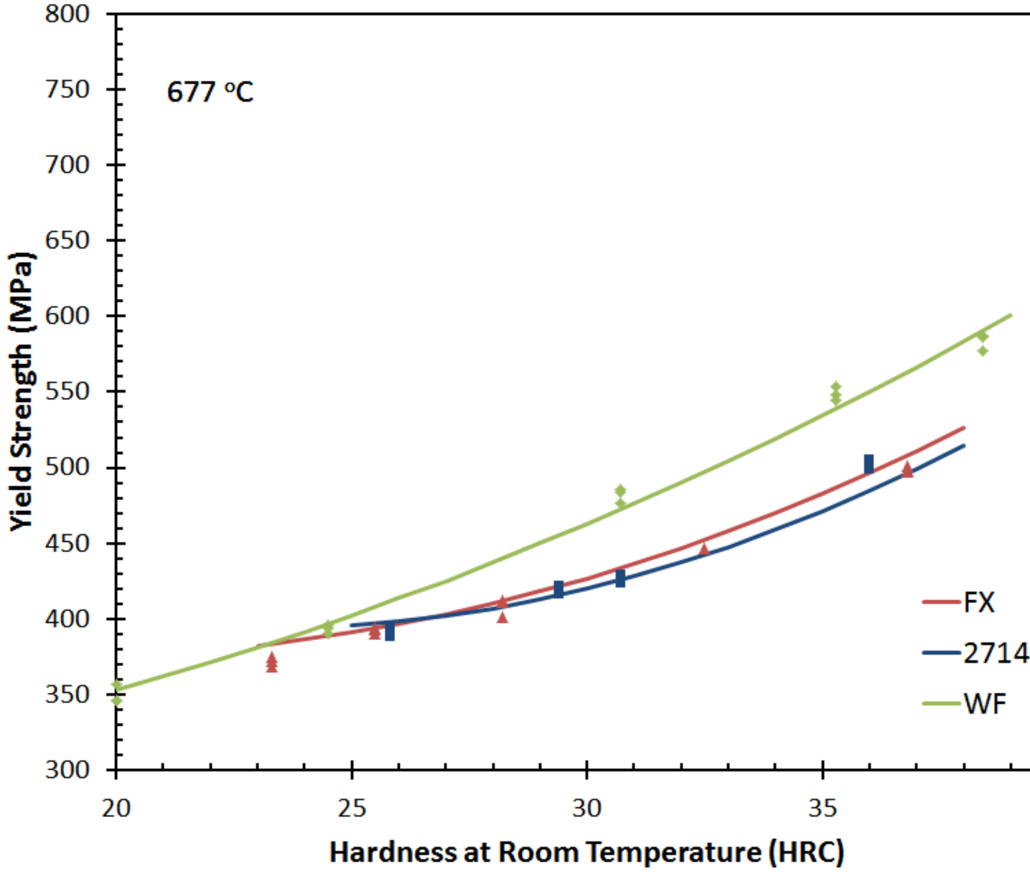

Figure 5 Comparison of yield strengths for the three steels at 677 °C.

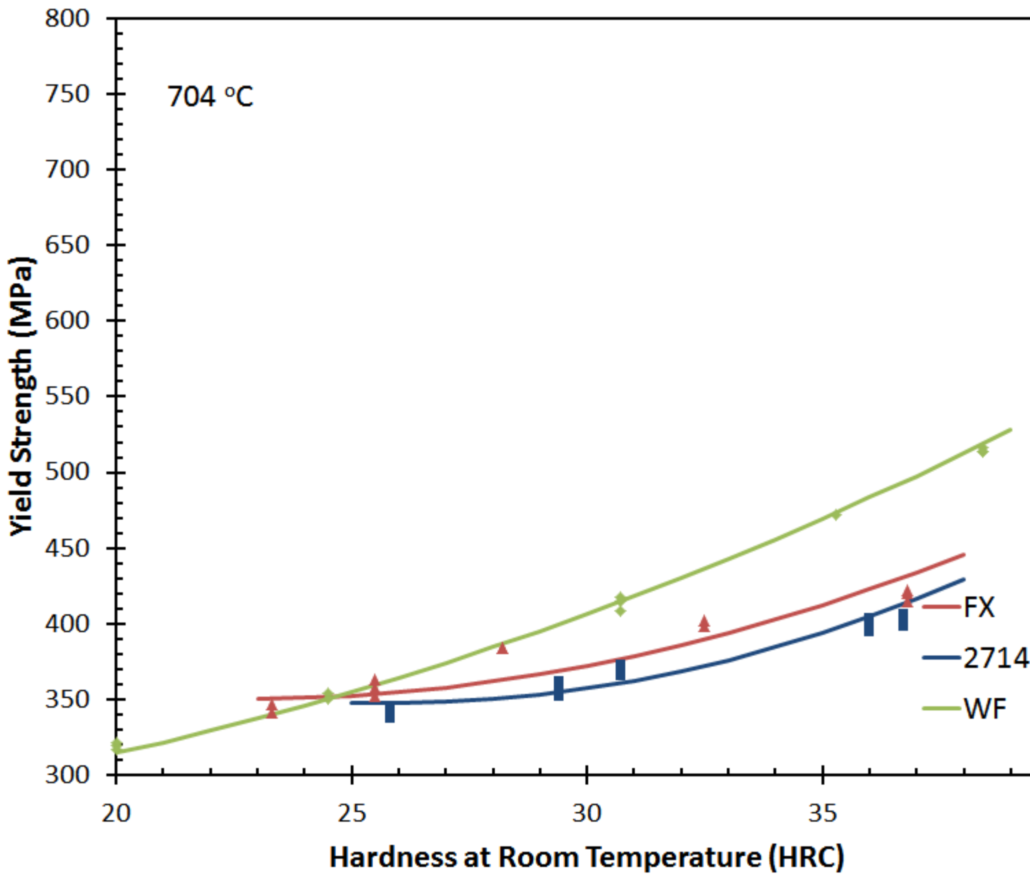

Figure 6 Comparison of yield strengths for the three steels at 704 ^{o}C.