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Fatigue Behavior, Monotonic Properties and Microstructure Data for Quenched and Tempered 51B60 Steel

(Iteration No. 33)

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SUMMARY

The required chemical analysis, microstructure data, mechanical properties, cyclic stress-strain data and strain-controlled fatigue data for 51B60, Quenched and Tempered steel (Iteration No. 33) have been obtained. The material was provided by the American Iron and Steel Institute (AISI) in the form of 3.25" bars. These bars were machined into smooth axial fatigue specimens. The specimens were heat treated, quenched in oil and tempered before received to give a hardness of about Rc 45. Two monotonic tensile tests were performed to measure the yield strength, the tensile strength and the reduction of area. Eighteen specimens were fatigue tested in laboratory air at room temperature to establish a strain-life curve.

INTRODUCTION

This report presents the results of tensile and fatigue tests performed on a group of 20 Quenched and Tempered 51B60 steel samples. The material was provided by the American Iron and Steel Institute.

The objectives of this investigation were to obtain the chemical analysis, and microstructural data, mechanical properties, cyclic stress-strain data and strain-life fatigue data requested by the AISI bar group.

EXPERIMENTAL PROCEDURE

Specimen Preparation

The material for the study was received in the form of bars. Smooth cylindrical fatigue specimens, shown in Figure 1, were machined from the metal bars. The gauge sections of the fatigue specimens were mechanically polished in the loading direction using 240, 400, 500, and 600 emery paper. After polishing, a thin band of M-coat D acrylic coating was applied along the central gauge section. The purpose of the M-coat D application was to prevent scratching of the smooth surface by the knife-edges of the strain extensometer, thus reducing the incidence of knife-edge failures. In total, 20 fatigue data points were generated.

Test Equipment and Procedure

Two monotonic tension tests were performed to determine the yield strength, the tensile strength, the percent of elongation and the percent reduction of area. Hardness tests were performed on the surface of three fatigue specimens using a Rockwell C scale. The hardness measurements were repeated three times for each specimen and the average value was recorded.

All fatigue tests were carried out in a laboratory environment at approximately 25 ^{o}C using an MTS servo-controlled closed loop electrohydraulic testing machine. A process control computer, controlled by FLEX software [1] was used to output constant strain and stress amplitudes in the form of a sinusoidal wave.

Axial, constant amplitude, fully reversed (R=-1) strain-controlled fatigue tests were performed on smooth specimens. The stress-strain limits for a given cycle of each specimen were recorded at logarithmic intervals throughout the test via a peak reading oscilloscope. Failure of a specimen was defined as a 50 percent drop in tensile peak load from the peak load observed at one half the expected specimen life. For fatigue lives greater than 100,000 reversals, the specimens were tested in stress-control once the stress-strain loops had stabilized. For the stress-controlled tests, failure was defined as the separation of the smooth specimen into two pieces. For strain-controlled tests the loading frequency varied from 0.03 Hz to 5 Hz while in stress-controlled tests the frequency used was up to 110 Hz.

The first reversal of each fatigue test was recorded on a x-y plotter, allowing the elastic modulus (E) and the monotonic yield strength to be determined.

RESULTS

A) Microstructure Data

Figure 2 presents the martensitic microstructure of the 51B60, Quenched and Tempered steel. A Type D inclusion severity level of 1 was obtained based on ASTM E45 (Method A). Inclusions of types A, B, and C were not observed. Figure 3 shows the inclusions observed in the 51B60, Quenched and Tempered steel. The inclusion area was measured using a JAVA image analysis system. The chemical composition of 51B60, Quenched and Tempered steel was provided by the supplier North Star Steel Michigan Division, and is shown in Table 1.

B) Strain-Life Data

The fatigue test data for 51B60, Quenched and Tempered steel obtained in this investigation are given in Table 2. The stress amplitude corresponding to each strain-amplitude was calculated from the peak load amplitude at the specimen half-life.

A fatigue strain-life curve for the 51B60, Quenched and Tempered steel is shown in Figure 4, and is described by the following equation:

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma'_f}{E}(2N_f)^b + \varepsilon'_f(2N_f)^c$$

where

$\frac{\Delta\varepsilon}{2}$	= True total strain amplitude
$2N_f$	= Number of reversals to failure
σ'_f	= Fatigue strength coefficient
b	= Fatigue strength exponent
ε'_f	= Fatigue ductility coefficient
c	= Fatigue ductility exponent

Where σ'_f = 2582 MPa, b = -0.0833, ε'_f = 0.451 and c = -0.6396. These values of the strain-life parameters were determined from fatigue testing over the range: $0.0037 < \frac{\Delta\varepsilon}{2} < 0.01$.

C) Cyclic Stress-Strain Curves

Stabilized and half-life stress data obtained from strain-life fatigue tests were used to obtain the companion cyclic stress-strain curve shown in Figure 5. The true cyclic stress-strain curve is described by the following equation:

$$\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{K'}\right)^{\frac{1}{n'}}$$

where

ε	= True total strain amplitude
σ	= Cyclically stable true stress amplitude
K'	= Cyclic strength coefficient
n'	= Cyclic strain hardening exponent

Where K' = 2490 MPa and n' = 0.108.

D) Mechanical Properties

The engineering monotonic stress-strain curve is given in Figure 6. The monotonic and cyclic properties are included in Appendix 1. The Hardness of the 51B60, Quenched and Tempered steel taken as the average of three randomly chosen fatigue specimens and is given in Appendix 1. The individual hardness measurements are also given in Table 2. The true monotonic and true cyclic stress-strain curves plotted together are given in Figure 7.

REFERENCES

[1] Pompetzki, M.A., Saper, R.A., and Topper, T.H., "Software for High Frequency Control of Variable Amplitude Fatigue Tests," Canadian Metallurgical Quarterly, Vol. 25, No. 2, pp. 181-194, 198.

[2] J. A. Bannantine, J. J. Comer, and J. L. Handrock (1990), In :Fundamentals of Metal Fatigue Analysis, Prentice Hall, London.

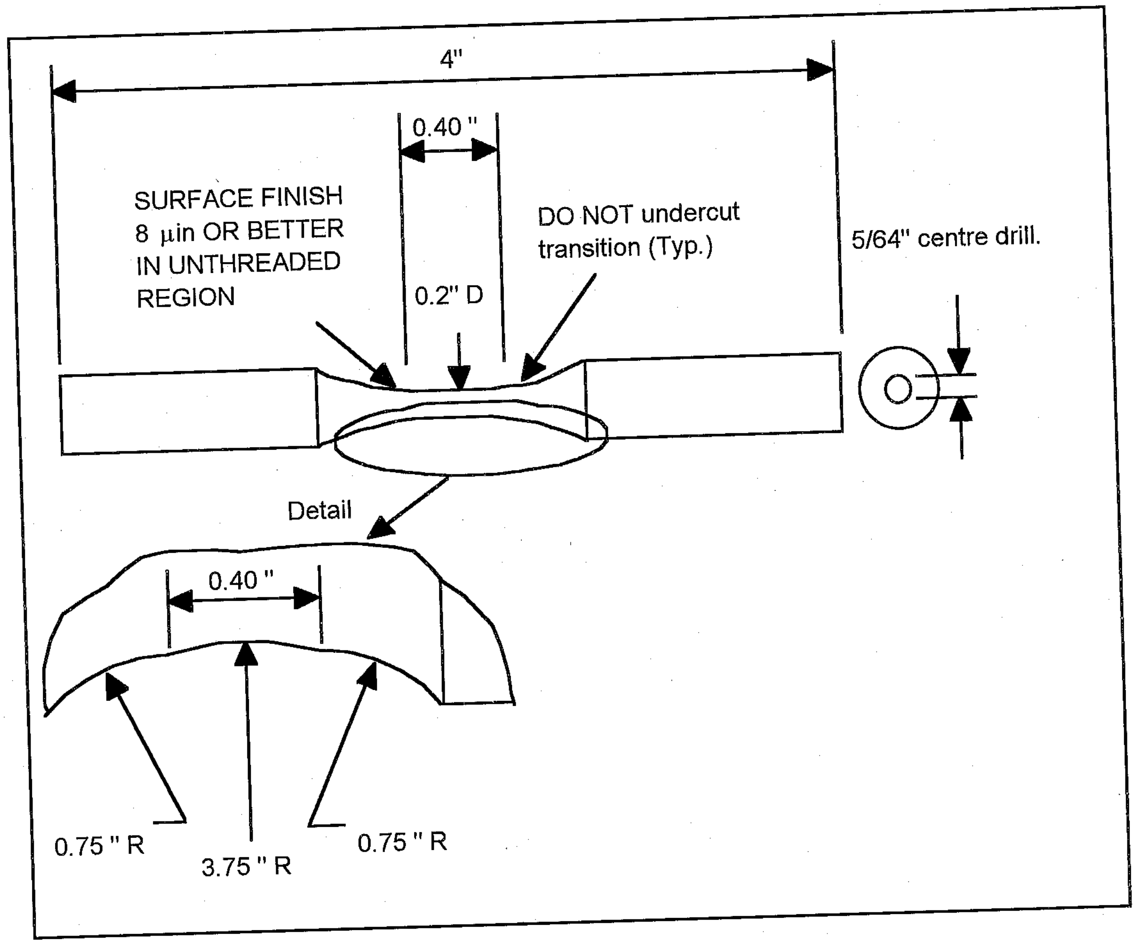


Fig. 1 Smooth cylindrical fatigue specimen

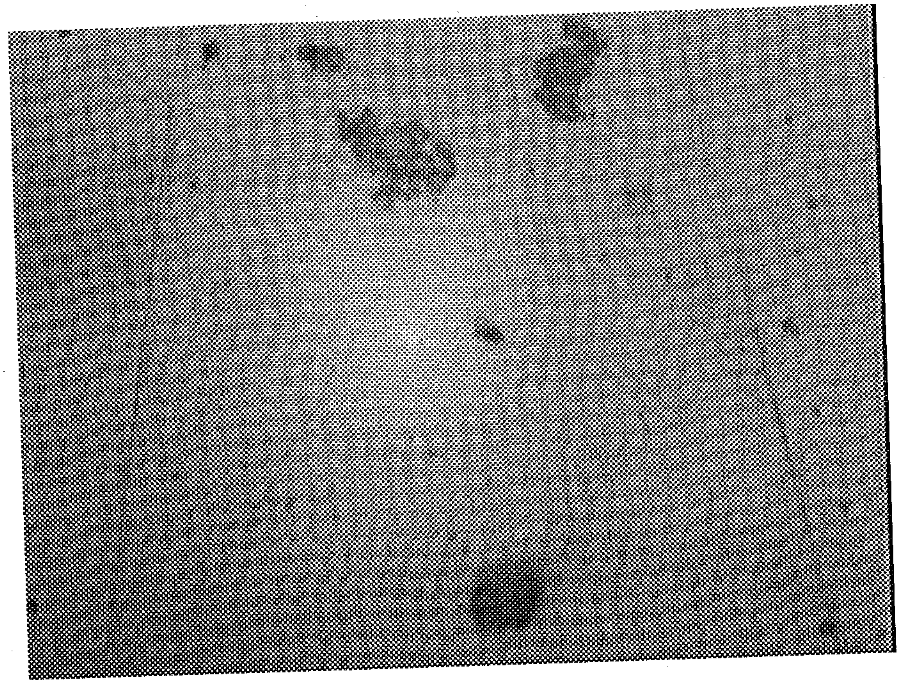


Fig. 3 Inclusions photomicrograph of 51B60, Quenched and Tempered steel (X500)

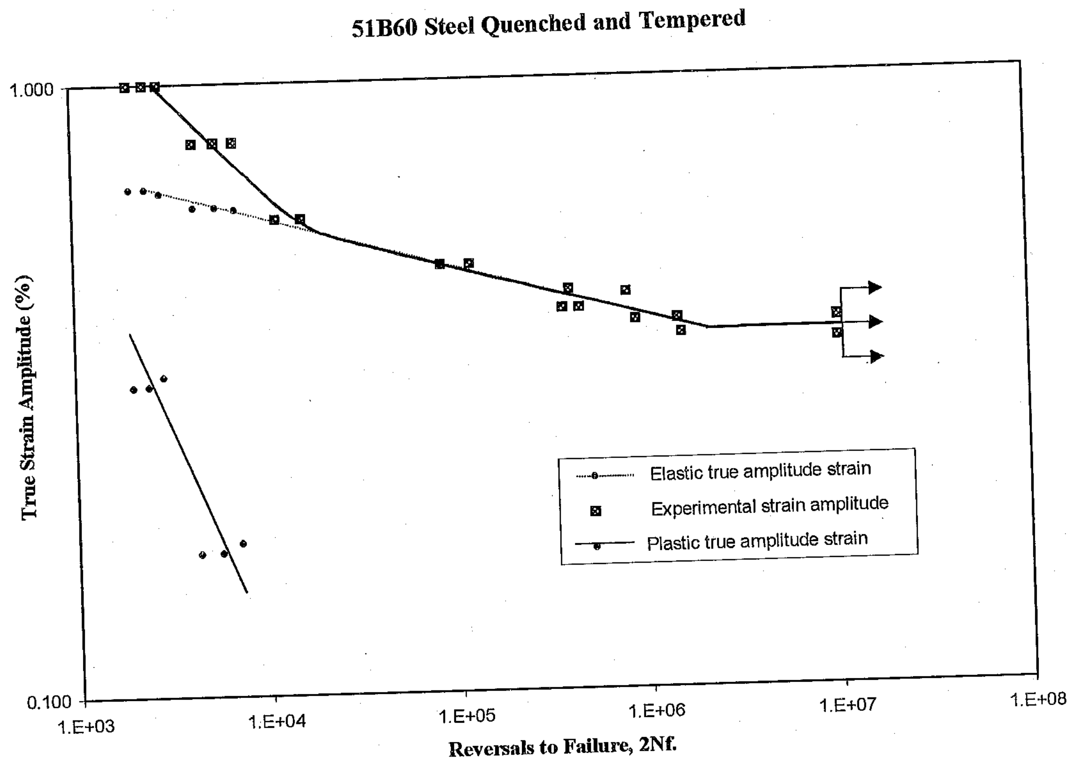


Figure 4. Constant amplitude fully reversed strain-life curve for 51B60, Quenched and Tempered steel.

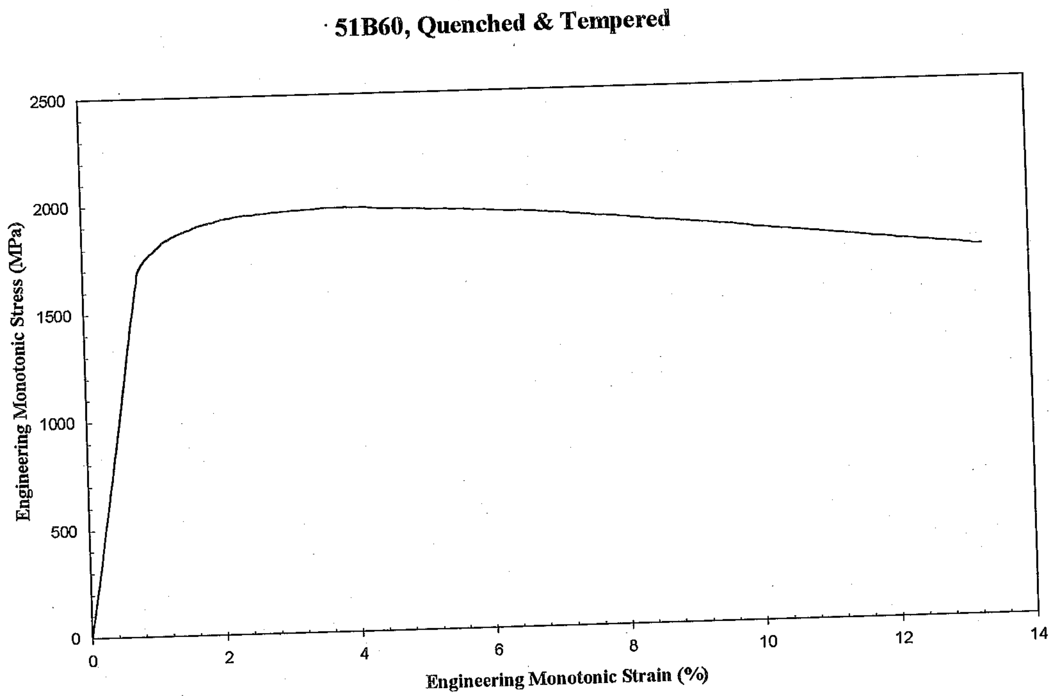


Figure 5. Monotonic stress-strain curve for 51B60, Quenched and Tempered steel.

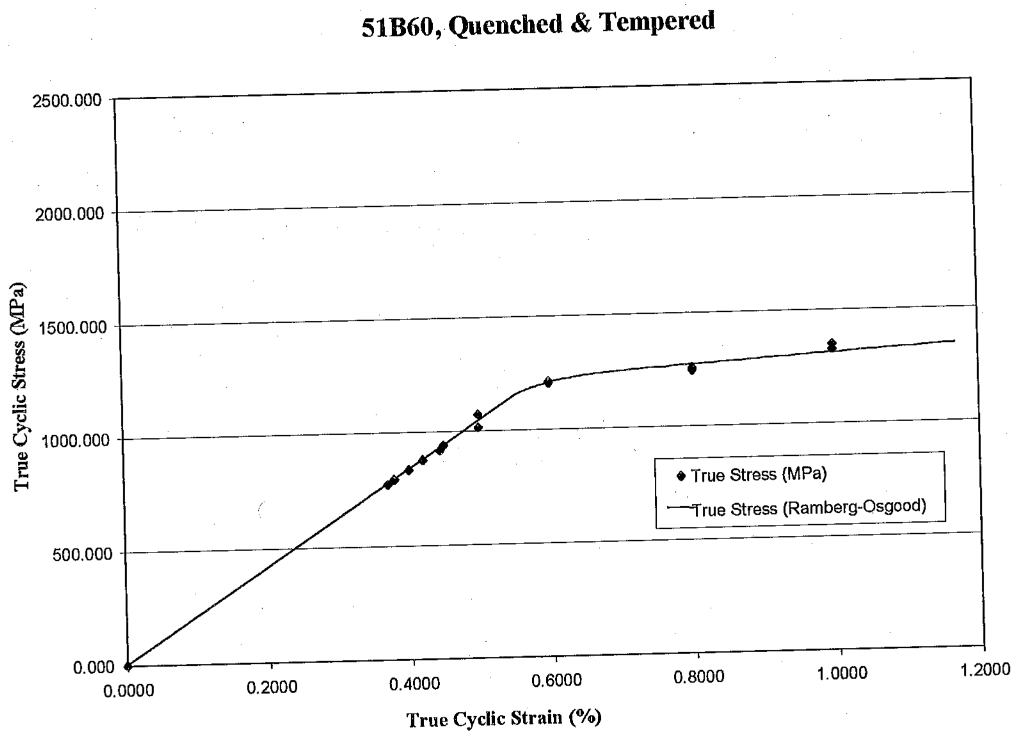


Figure 6. Cyclic stress-strain curve for 51B60, Quenched and Tempered steel.

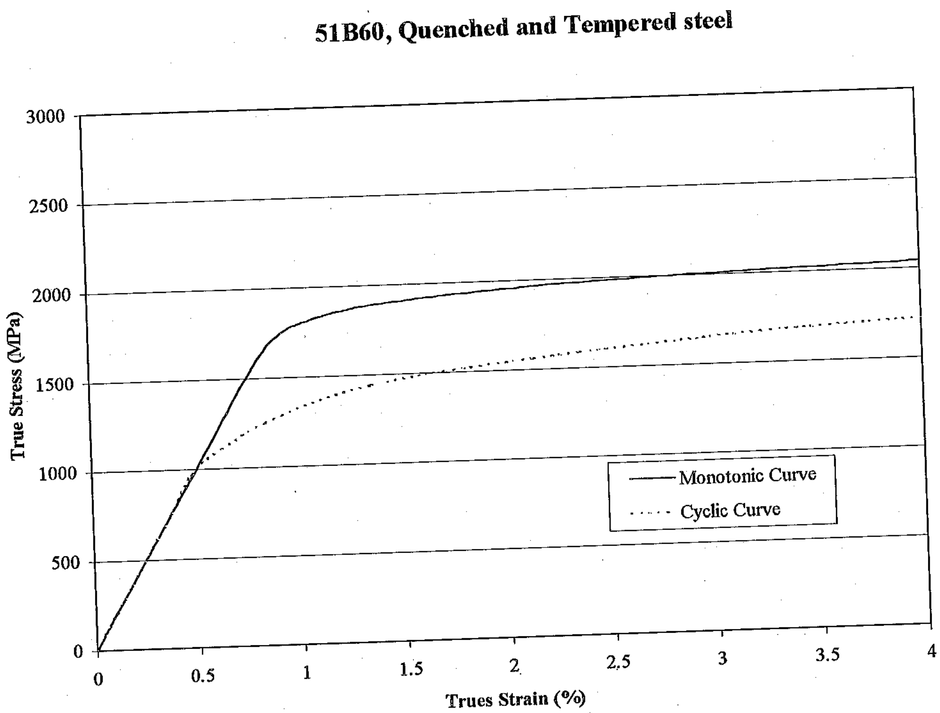


Fig. 7 Monotonic and Cyclic stress-strain curves for 51B60, Quenched and Tempered steel.

Table 1 Chemical composition of 51B60, Quenched and Tempered steel.

Carbon, C	0.587%
Manganese, Mn	0.86%
Phosphorous, P	0.008%
Sulfur, S	0.013%
Silicon, Si	0.26%
Copper, Cu	0.1%
Nickel, Ni	0.07%
Chromium, Cr	0.81%
Molybdenum, Mo	0.04%
Sn	0.006%
Al	0.027%
Vanadium, Va	0.008%
Nb	0.003%
Ti	0.041%
B	0.0021%
Zn	0.0019%
Pb	0.0035%
Co	0.0059%

Table 2 Tensile and Fatigue Test Data for 51B60, Quenched and Tempered steel.

Sp#	Total Strain Amplitude(%)	Stress Amplitude (MPa)	Plastic Strain Amplitude(%)	Elastic Strain Amplitude(%)	(50% load drop) Fatigue Life (Reversals, 2Nf)	MONOTONIC Young's Modulus(GPa)	Hardness (HRC)
6	0.996	1349	0.322	0.674	1998	190	42
12	0.998	1327	0.334	0.664	2870	190	43
17	0.997	1349	0.322	0.675	2416	201	45
19	0.800	1256	0.172	0.628	5602	200	45
26	0.801	1249	0.178	0.623	7060	193	43
24	0.799	1256	0.171	0.628	4324	200	44
23	0.598	1208	0.000	0.598	17014	202	46
25	0.598	1203	0.000	0.598	15802	204	48
8	0.498	1072	0.000	0.498	120000	200	44
2	0.498	1015	0.000	0.498	84880	203	47
1	0.449	939	0.000	0.449	397400	207	48
7	0.443	918	0.000	0.443	793076	207	48
15	0.419	876	0.000	0.419	366782	200	45
27	0.419	876	0.000	0.419	446926	200	46
24*	0.399	833	0.000	0.399	10000000	204	44
14*	0.398	834	0.000	0.398	10000000	206	47
30	0.399	833	0.000	0.399	882912	198	45
20	0.400	834	0.000	0.400	1472236	200	45
4	0.379	792	0.000	0.379	1532132	195	42
10*	0.369	771	0.000	0.369	10000000	200	43

* Run out

Appendix 1

Monotonic Properties for 51B60, Quenched and Tempered steel.

Average Elastic Modulus, E	=	200.03 GPa
Yield Strength	=	1830 MPa
Ultimate tensile Strength	=	1970 MPa
% Elongation	=	36.15 %
% Reduction of Area	=	21.55 %
True fracture strain, $Ln\ (A_i / A_f)$	=	23.14 %
True fracture stress, $\sigma_f = \dfrac{P_f}{A_f}$	=	2173 MPa

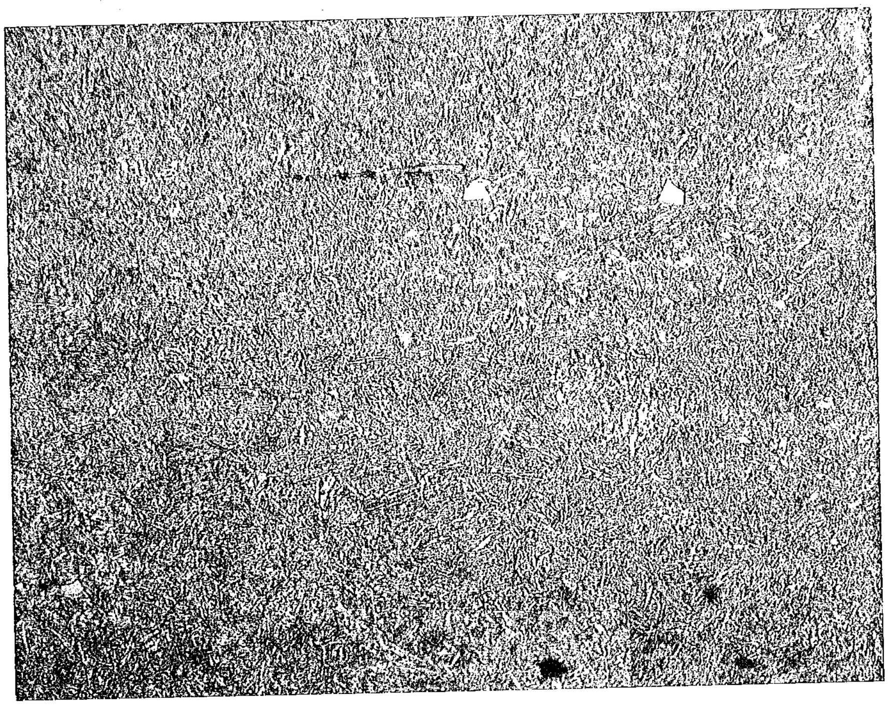
Bridgman correction, $\sigma_f = \dfrac{P_f}{A_f} \Big/ \left(1+\dfrac{4R}{D_f}\right) Ln\left(1+\dfrac{D_f}{4R}\right)$ =1968MPa

Monotonic strength coefficient, K	=	2332 MPa
Monotonic strain hardening exponent, n	=	0.0387
Hardness, Rockwell C (HRC)	=	45
Hardness, Brinell	=	450

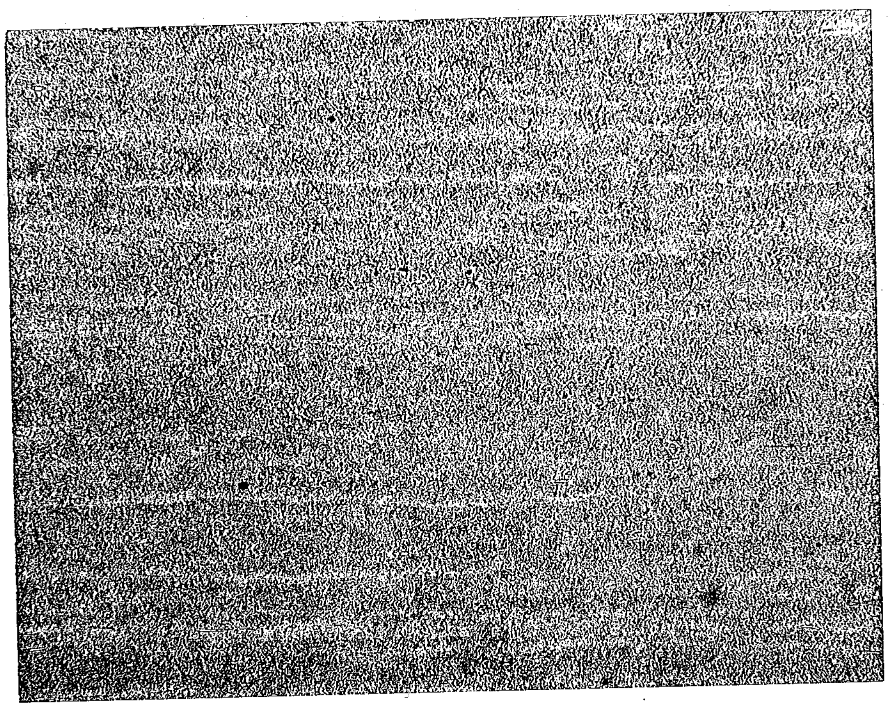
Cyclic Properties for 51B60, Quenched and Tempered steel.

Cyclic Yield Strength, (0.2% offset)= $K'(0.002)^{n'}$	=	1272 MPa
Cyclic strength coefficient, K'	=	2490 MPa
Cyclic strain hardening exponent, n'	=	0.108
Fatigue Strength Coefficient, σ'_f	=	2582 MPa
Fatigue Strength Exponent, b	=	-0.0833
Fatigue Ductility Coefficient, ε'_f	=	0.4518
Fatigue Ductility Exponent, c	=	-0.6396

P_f:	Load at fracture.
A_i and A_f:	Specimen cross-section area before and after fracture.
R:	Specimen neck radius.
D_f	Specimen diameter at fracture.



ITER 33: Photomicrograph of SAE 51B60 steel, Quenched and Tempered to Rc-45. 500X Mag.



ITER 33: Photomicrograph of SAE 51B60 steel, Quenched and Tempered to Rc-45. 100X Mag.

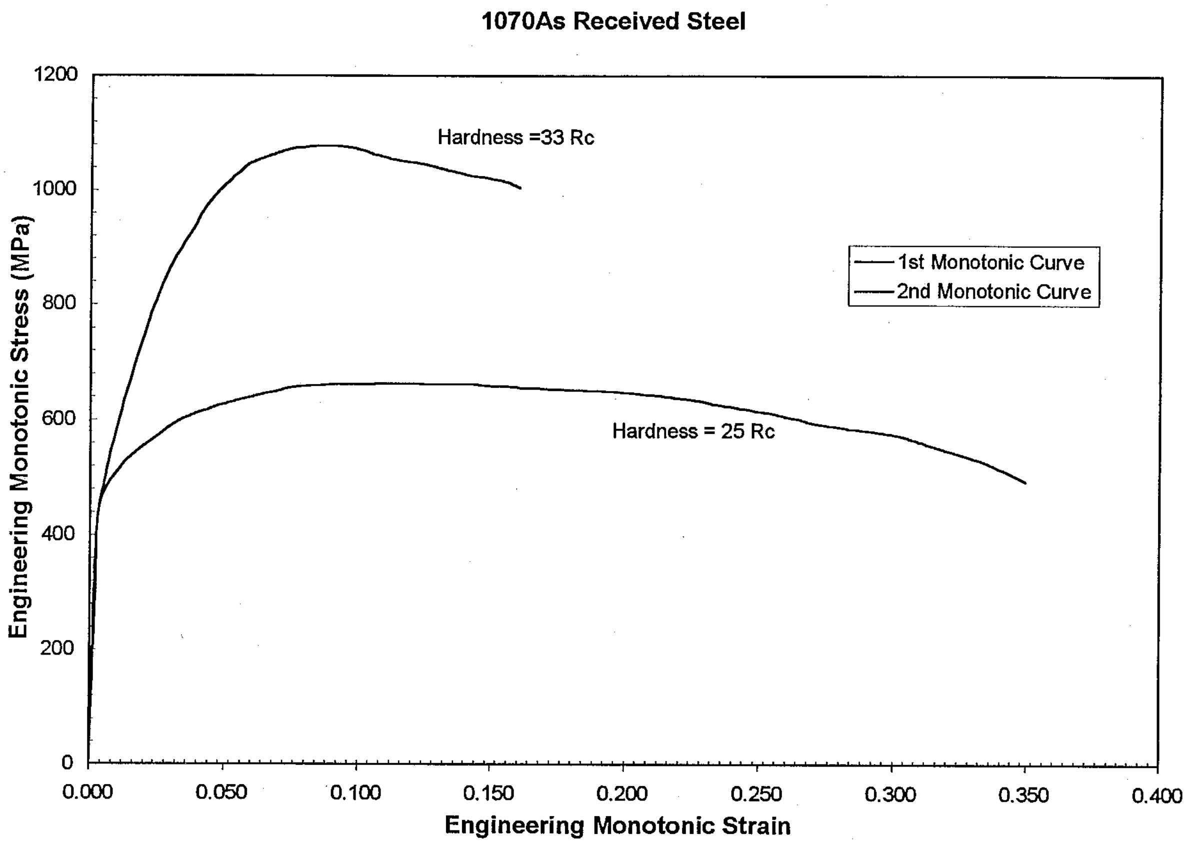


Figure 5. Monotonic stress-strain curve for 1070 As Received steel.