AISI 1090
Quenched and Tempered Steel
Iteration #8

Fatigue Behavior, Monotonic Properties and Microstructural Data

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Prepared for:
The AISI Bar Steel Applications Group

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SUMMARY

The required chemical analysis, microstructural data, mechanical properties, cyclic stress-strain data and strain-controlled fatigue data for AISI 1090 Quenched and Tempered steel (Iteration # 8) have been obtained. The material was provided by the American Iron and Steel Institute (AISI) in the form of metal bars. These bars were machined into smooth axial fatigue specimens. A monotonic tensile test was performed to measure yield strength, tensile strength and reduction of area. Twenty one 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 22 Quenched and Tempered 1090 steel samples. The material was provided by the American Iron and Steel Institute.

The objectives of this investigation were to obtain a chemical analysis, and the microstructural data, mechanical properties, cyclic stress-strain data and strain-life tests 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, 21 fatigue data points were generated.

Test Equipment and Procedure

A monotonic tension test was 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 30 Hz.

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

RESULTS

A) Microstructural Data

Figure 2 presents the Martensite microstructure of AISI 1090 Quenched and Tempered steel. A type A inclusion rate of $\frac{1}{2}$ was obtained based on the severity level number according to ASTM E45 method A. Inclusions of types B, C, and D were not observed. Figure 3 presents the observed inclusions of AISI 1090 quenched and tempered steel. The inclusion area was measured using a JAVA image analysis system. The chemical composition of AISI 1090 quenched and tempered steel was provided by SCI-Lab materials testing inc., 25 Mclntyre place, unit 2, Kitchener, Ontario, N2R 1H1, and is shown in Table 1.

B) Strain-Life Data

The fatigue test data for AISI 1090 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 one half the expected specimen life.

A fatigue strain-life curve for the AISI 1090 quenched and tempered steel is shown in Figure 4, and may 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 =1858 MPa, **b** = -0.1157, ε'_f = 0.4488 and **c** = -0.5723. These values of the strain-life parameters were determined from fatigue testing over the range: $0.002 < \frac{\Delta\varepsilon}{2} < 0.01$.

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'** = 1913 MPa and **n'** = 0.1680.

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 AISI 1090 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.

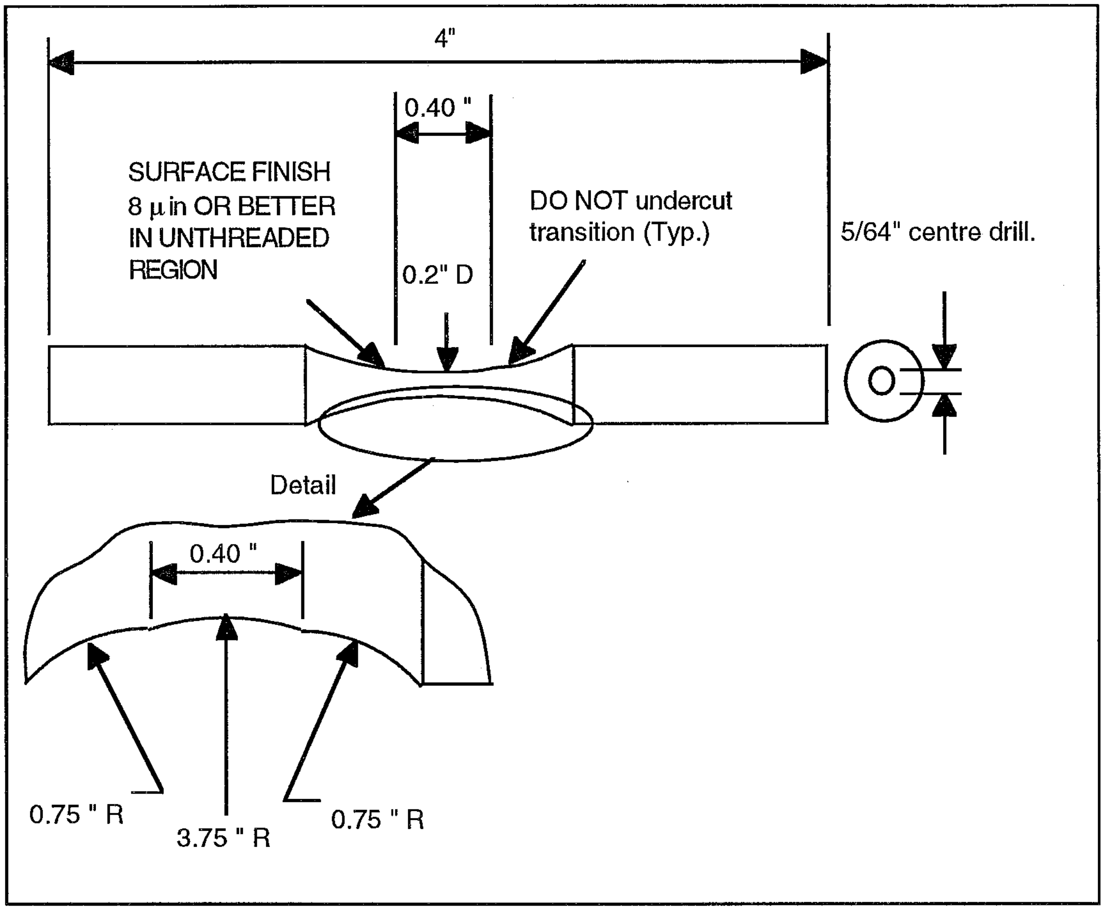
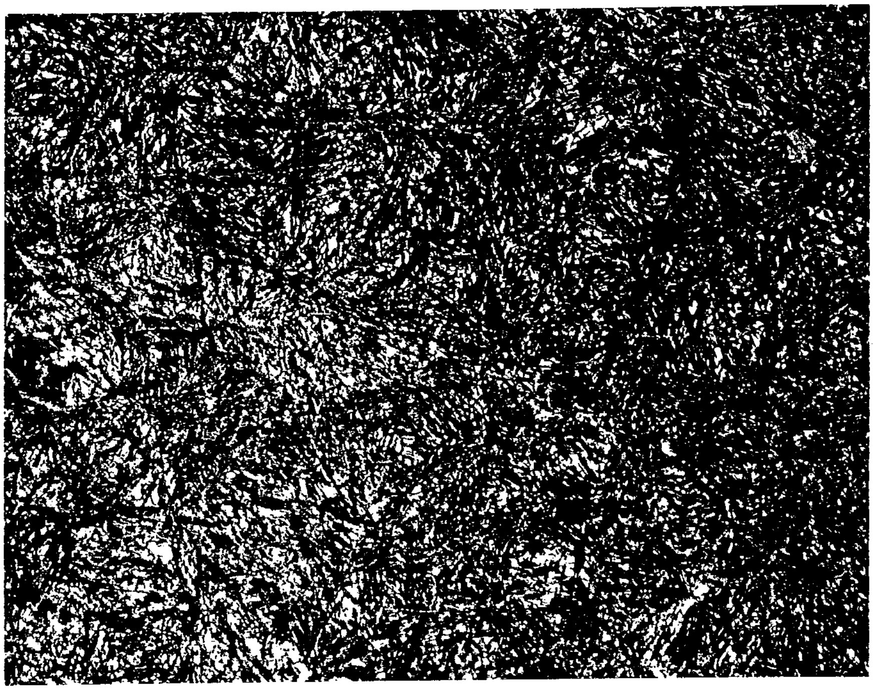
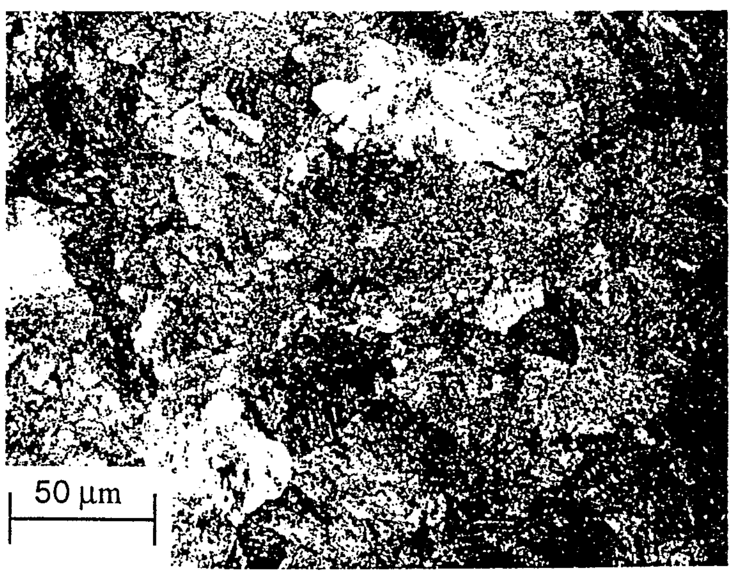


Fig. 1 Smooth cylindrical fatigue specimen



ITER 8: Photomicrograph of SAE 1090 steel, Quenched and Tempered to Rc-33. 500X Mag.



(b) Transverse direction

Fig. 2 Photomicrograohs of AISI 1090 quenched and tempered steel (X500): (a) Longitudinal direction, and (b) Transverse direction.

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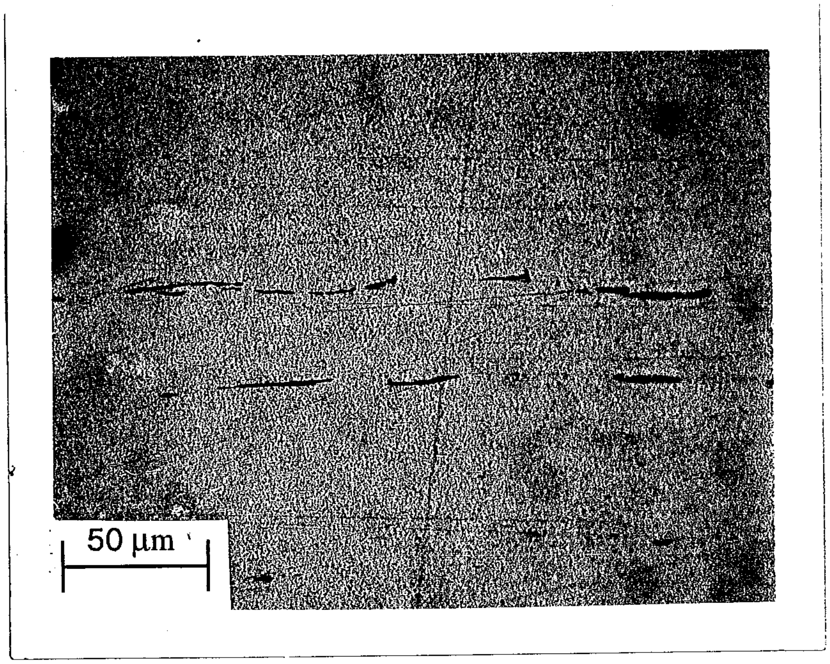
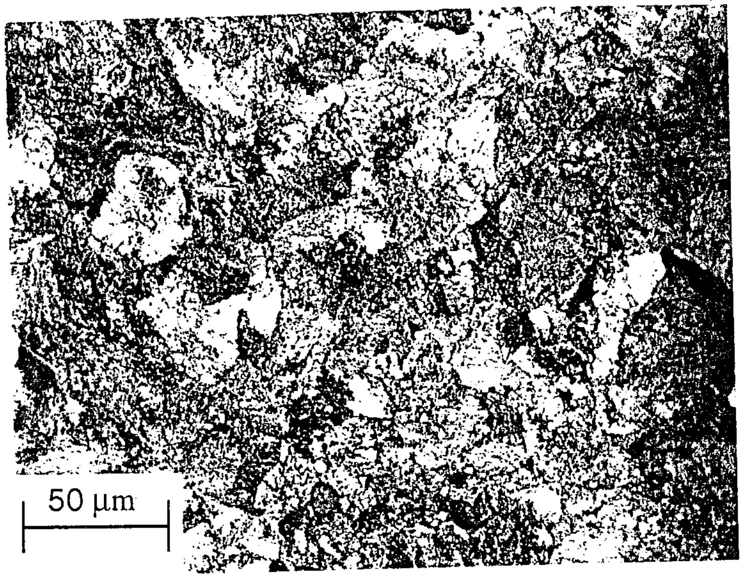
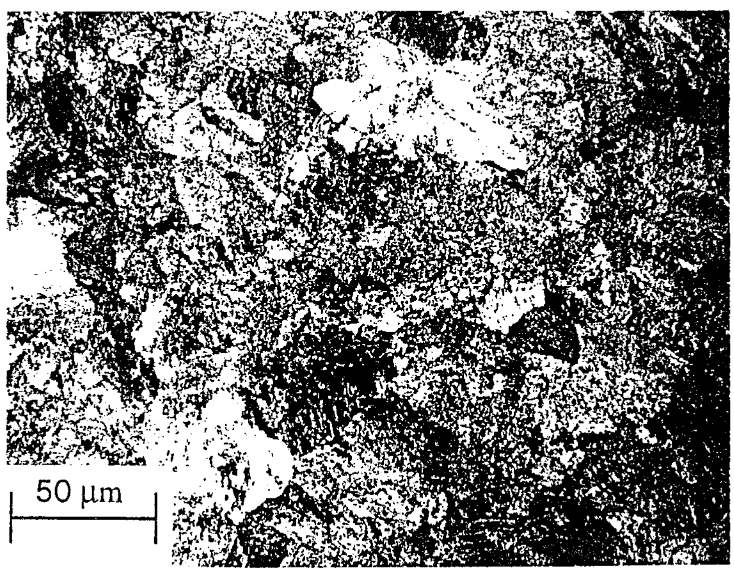


Fig. 3 Inclusions photomicrograoh of AISI 1090 quenched and tempered steel (X500)



(a) Longitudinal direction



(b) Transverse direction

Fig. 2 Photomicrograohs of AISI 1090 quenched and tempered steel (X500):
(a) Longitudinal direction, and (b) Transverse direction.

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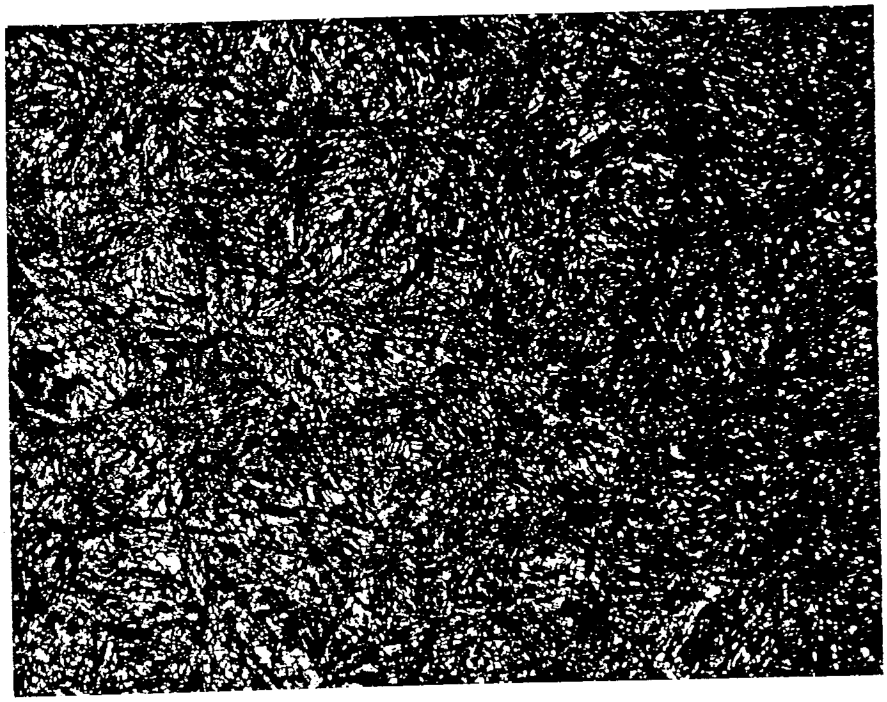

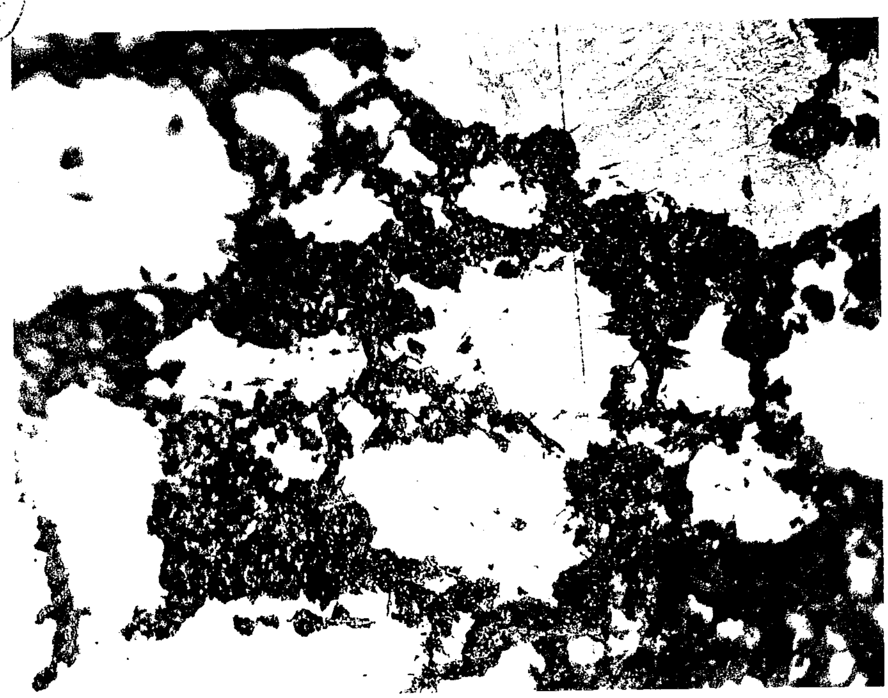

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Poor Quench

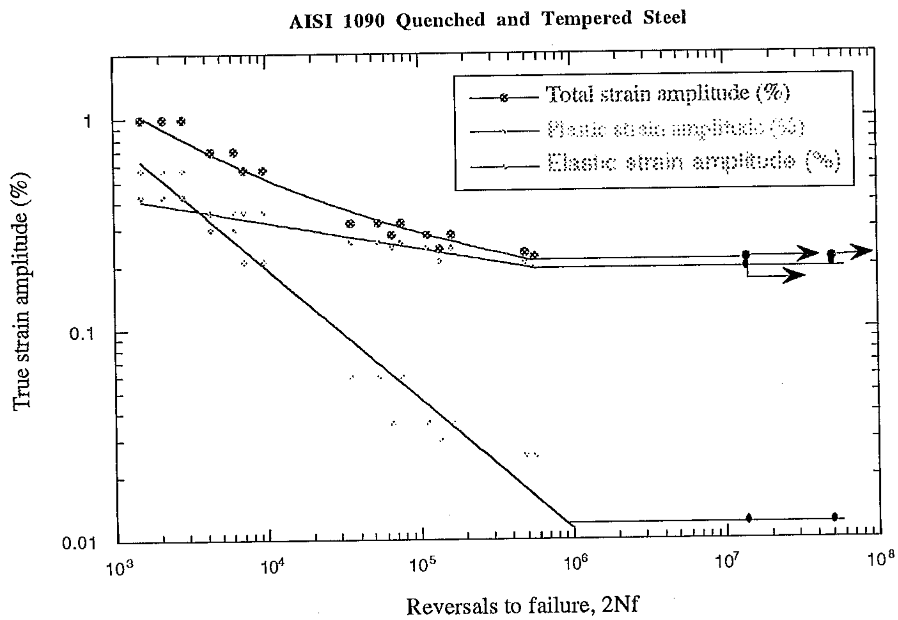

Fig. 4 Constant amplitude fully reversed strain-life curve for AISI 1090 quenched and tempered steel.

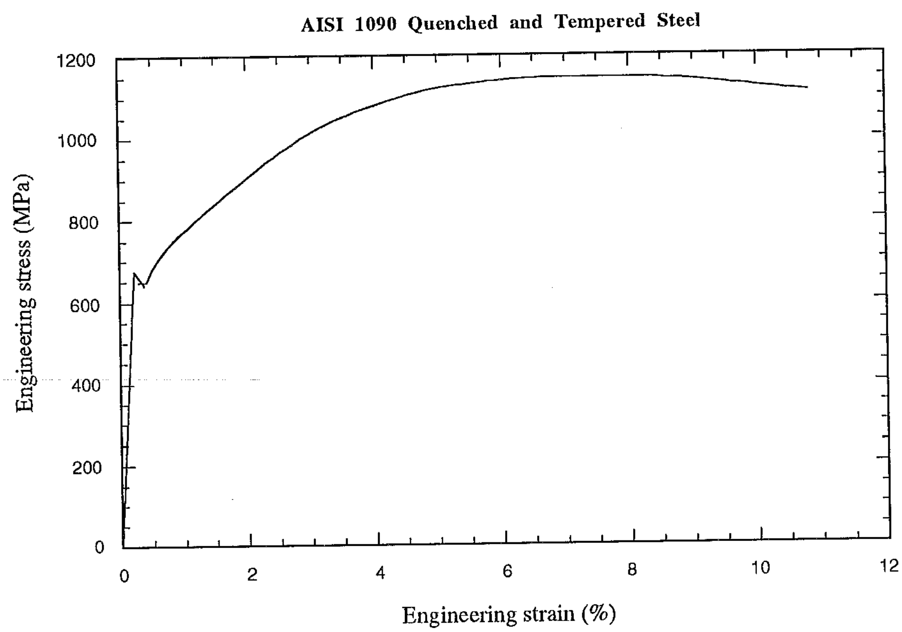

Fig. 5 Monotonic stress-strain curve for AISI 1090 quenched and tempered steel

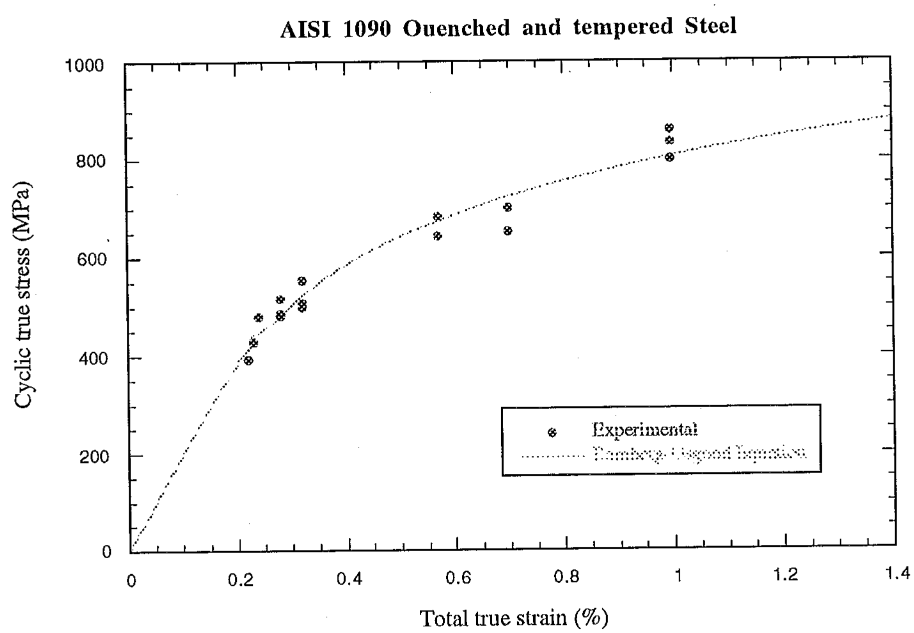

Fig. 6 Cyclic stress-strain curve for AISI 1090 quenched and tempered steel

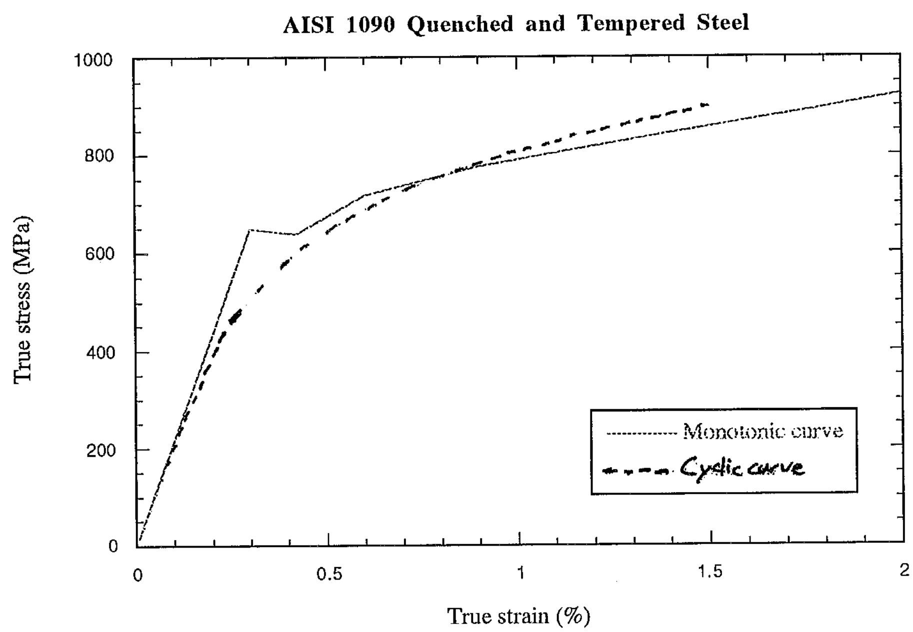

Fig. 7 Monotonic and Cyclic stress-strain curves for AISI 1090 quenched and tempered steel

Table 1 Chemical composition of AISI 1090 quenched and tempered Steel

Carbon, C	0.88%
Manganese, Mn	0.66%
Phosphorous, P	0.001%
Sulfur, S	0.019%
Silicon, Si	0.18%
Copper, Cu	0.08%
Nickel, Ni	0.04%
Chromium, Cr	0.07%
Molybdenum, Mo	0.01%
Vanadium, Va	0.037%
Calcium, Ca	0.001%
Boron, Bo	0.003%
Aluminum, Al	<0.001%
Titanium, Ti	0.001%
Oxygen, O	0.0028%
Columbium, Cb	0.003%

Table 2 Tensile and Fatigue Test Data for 1090 quenched and tempered Steel

Spec	TRUE Total Strain Amplitude(%)	TRUE Stress Amplitude (MPa)	TRUE Plastic Strain Amplitude(%)	TRUE Elastic Strain Amplitude(%)	(50% load drop) Fatigue Life (Reversals, 2Nf)	MONOTONIC Young's Modulus(GPa)	Hardness (HRC)
QT3	0.995	815.96	0.618	0.379	1500	216.82	
QT26	0.995	824.55	0.614	0.383	2800	234.15	
QT12	0.995	807.37	0.622	0.375	2100	204.88	
QT17	0.697	689.36	0.377	0.321	6126	202.58	33
QT27	0.697	685.08	0.379	0.319	4300	219.50	33
QT1	0.697	700.07	0.372	0.326	4280	219.50	
QT25	0.568	645.71	0.267	0.301	7104	191.52	
QT5	0.568	643.57	0.268	0.300	7080	191.52	
QT29	0.568	660.68	0.260	0.308	9454	219.50	
QT15	0.319	503.34	0.083	0.235	35290	219.50	
QT9	0.319	543.86	0.064	0.254	76006	219.50	
QT8	0.319	499.08	0.085	0.233	53744	219.50	
QT19	0.279	479.69	0.054	0.224	113320	219.51	
QT10	0.279	515.93	0.037	0.241	162158	219.50	33
QT11	0.279	486.09	0.051	0.227	65672	219.50	
QT20	0.239	479.50	0.015	0.224	135586	234.15	
QT24	0.229	428.31	0.029	0.200	493542	219.50	
QT14	0.219	392.04	0.036	0.183	567808	219.50	
QT17	0.214	379.24	0.037	0.177	10000000*	191.52	
QT23	0.214	389.89	0.032	0.182	10000000*	191.50	
QT22	0.214	360.07	0.046	0.168	10000000*	191.50	

* Run out

Appendix 1

Monotonic Properties for AISI 1090 Quenched and Tempered Steel

Average Elastic Modulus, E	=	212.60 GPa
Upper Yield Strength	=	647.57 MPa
Lower Yield Strength	=	634.40 MPa
Monotonic Yield Strength (0.2% offset)	=	677.55 MPa
Ultimate tensile Strength	=	1147 MPa
% Elongation	=	66.66 % — ? 6.7%
% Reduction of Area	=	21.68 %
True fracture strain, $Ln\ (A_i / A_f)$	=	24.5 %
True fracture stress, $\sigma_f = \frac{P_f}{A_f}$	=	1400 MPa

Bridgman correction, $\sigma_f = \frac{P_f}{A_f} \Big/ \left(1+\frac{4R}{D_f}\right) Ln\left(1+\frac{D_f}{4R}\right)$ =1151 MPa

Monotonic strength coefficient, K	=	1913 MPa
Monotonic strain hardening exponent, n	=	0.1680
Hardness, Rockwell (HRC)	=	33 HRC
Hardness, Brinell	=	309

Cyclic Properties for AISI 1090 Quenched and Tempered Steel

Cyclic Yield Strength, (0.2% offset) $= K'(0.002)^{n'}$	=	617.90 MPa
Cyclic strength coefficient, K'	=	2162.80 MPa
Cyclic strain hardening exponent, n'	=	0.2016
Fatigue Strength Coefficient, σ'_f	=	1858 MPa
Fatigue Strength Exponent, b	=	-0.1157
Fatigue Ductility Coefficient, ε'_f	=	0.4488
Fatigue Ductility Exponent, c	=	-0.5723

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.

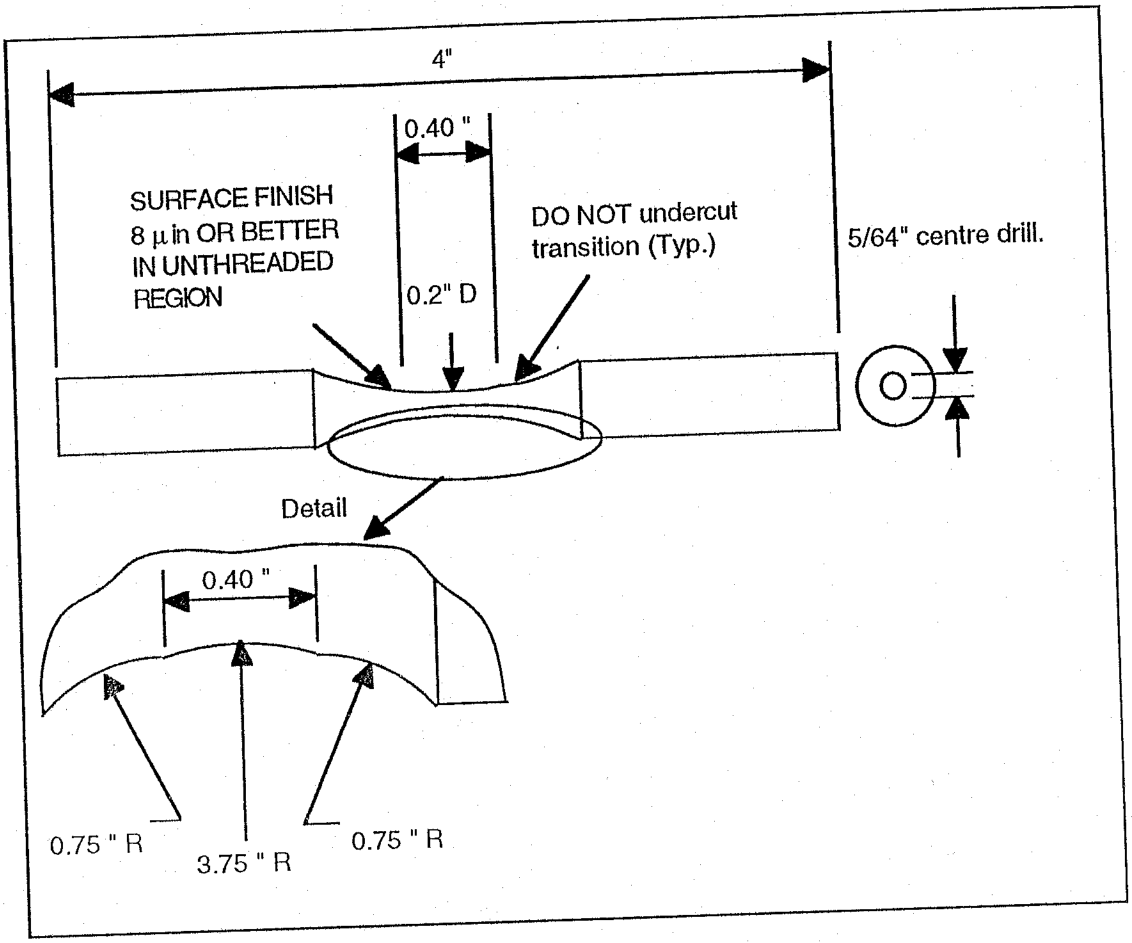

Fig. 1 Smooth cylindrical fatigue specimen

AISI Bar Application Group Fatigue Project
Test Matrix (6-9-98)

Iter. No.	Steel	Supplier	Status	Part Fabrication	Fabricated Hdns	Microstructure	School	Bar or Part
1	1541	RES	Complete 2-4-98	Normalize 1650F		Ferrite/Pearlite	Waterloo	HR Bar
2	1541	RES	Complete 2-4-98	Cold Size/Form	Rb 85 min.	Ferrite/Pearlite	Waterloo	HR Bar
3	1050M	Stelco	Complete 7-30-97	Normalize 1650F		Ferrite/Pearlite	Waterloo	Hr Bar
4	1050M	Chrysler	Complete 6-9-98	Hot Forge, Cold Extrude (Core)	Rc 35 max.	Martensite	Waterloo	Axles
5	1050M	Chrysler	Complete 6-9-98	Induction Surface Hardened (Case)	Rc 58 min.	Martensite	Waterloo	Axles
6	1090	NS	Complete 6-9-98	Normalize 1650F		Pearlite	Waterloo	Hr Bar
7	1090M	Chrysler	Complete 6-9-98	Hot Form + Acc. Cool	BHN 341-444	Martensite/Bainite	Waterloo	Stab Bar
8	1090	Chrysler	Complete 2-4-98	Hot Form + Q&T	BHN 341-444	Martensite	Waterloo	Stab Bar
9*	1090M	GM/AMM	Complete 2-4-98	Hot Form + Acc. Cool	BHN 302-363	Martensite/Bainite	Waterloo	Stab Bar
10*	1090	GM/Mather	Complete 6-9-98	Hot Form + Austemper	BHN 3.0-3.5	Bainite	Waterloo	Stab Bar
11	1141(AlFG)	RES	Complete 6-9-98	Normalize 1650F		Ferrite/Pearlite	Toledo	Hr Bar
12	1141(AlFG)	RES	Complete 6-9-98	Reheat, Q&T	BHN 229-269	Martensite	Toledo	Hr Bar
13	1141(NbFG)	NS	Complete 6-9/98	Normalize 1650F		Ferrite/Pearlite	Toledo	Hr Bar
14	1141(NbFG)	NS	Complete 6-9-98	Reheat, Q&T	BHN 229-269	Martensite	Toledo	Hr Bar
15	1141(VFG)	NS	@Toledo	Normalize 1650F		Ferrite/Pearlite	Toledo	Hr Bar
16	1141(VFG)	NS	@Toledo	Reheat, Q&T	BHN 229-269	Martensite	Toledo	Hr Bar
17	1141(VFG)	NS	@Toledo	Normalize @ High Temp (1750F)	TBD	Ferrite/Pearlite	Toledo	Hr Bar
18	1038	Stelco	Complete 10-9-97	Normalize 1650F		Ferrite/Pearlite	Toledo	Hr Bar
19	1038	Stelco	Complete 6-9-98	Cold Size/Form	Rb 85 min.	Ferrite/Pearlite	Toledo	Hr Bar
20	1038	Stelco	@Toledo-Re-H.T.	Reheat, Q&T, (Temper @ 930F)	Rc 20-30	Martensite	Toledo	Hr Bar
21	10V45	Inland	@Toledo	Normalized 1650F		Ferrite/Pearlite	Toledo	Hr Bar
22	10V45	Inland	@Toledo	Reheat, 2250F, Deform @ 2000F, FAC	RC 25-30	Ferrite/Pearlite	Toledo	Hr Bar

*These iterations will be supplied by GM, and funded separately from the rest of the program.

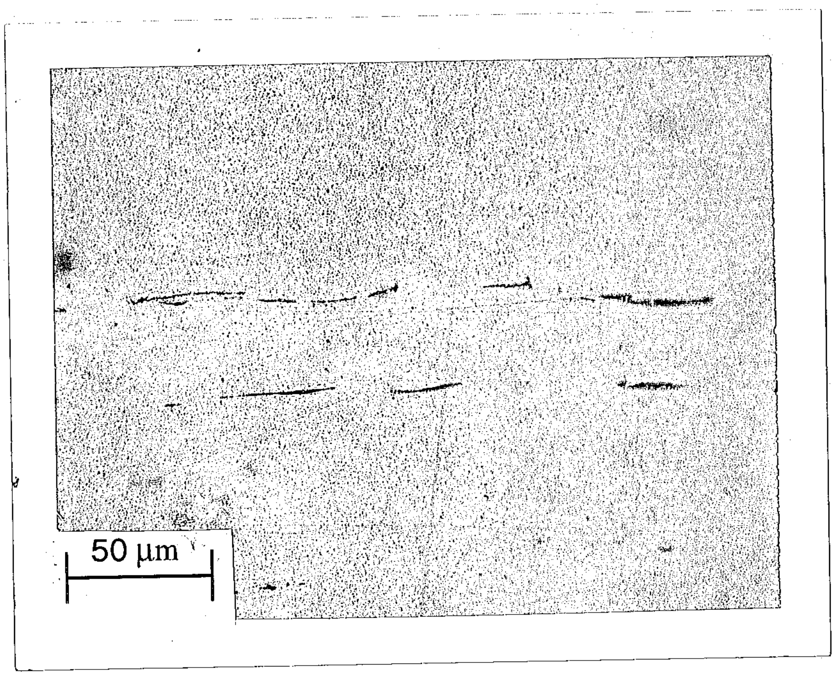

Fig. 3 Inclusions photomicrograoh of AISI 1090 quenched and tempered steel (X500)

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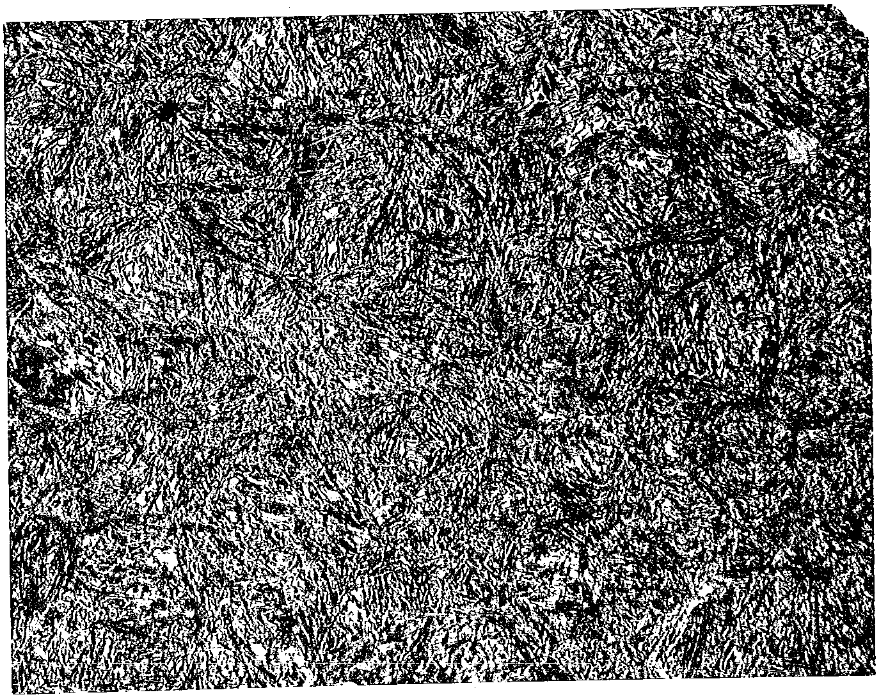

ITER 8: Photomicrograph of SAE 1090 steel, Quenched and Tempered to Rc-33. 500X Mag.

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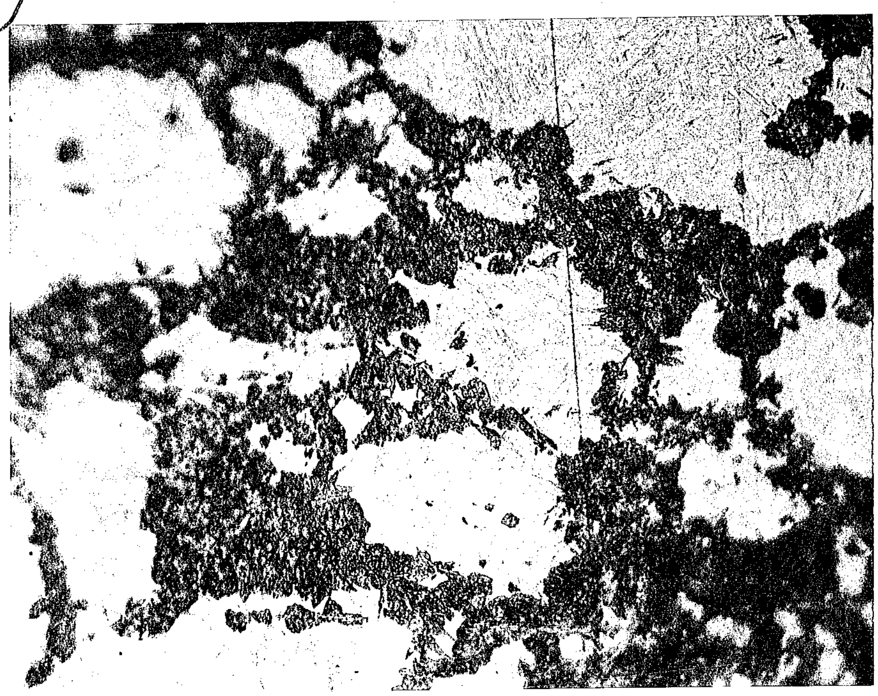

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Poor Quench