4140 Induction through Hardened Steel
Iteration #93

Fatigue Behavior, Monotonic Properties and Microstructural Data

Prepared by:

A.A. Rteil
and
T.H. Topper

Department of Civil Engineering
University of Waterloo
Waterloo, Ontario Canada

Prepared for:
The AISI Bar Steel Applications Group

November 2006

American Iron and Steel Institute

American Iron and Steel Institute
2000 Town Center, Suite 320
Southfield, Michigan 48075
tel: 248-945-4777
fax: 248-352-1740
www.autosteel.org

TABLE OF CONTENTS

SUMMARY

This report presents the monotonic and fatigue test results obtained for 4140 induction through hardened (It 93) steel. The material was provided by the American Iron and Steel Institute (AISI). Monotonic tensile tests were performed to measure the yield strength, the tensile strength and the reduction of area. Strain-controlled constant-amplitude fatigue tests were to obtain the strain-life curve, cyclic stress-strain curve and fatigue data for this material. Also the microstructure data was obtained.

INTRODUCTION

This report presents the results of tensile and fatigue tests performed on a group of 4140 induction through hardened (It 93) steel samples. The material was provided by the American Iron and Steel Institute. The objectives of this investigation were to obtain the microstructure 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 2.25” round bars. Smooth cylindrical fatigue specimens, shown in Figure 1, were machined from the cylindrical bars and induction hardened. Then, the gauge sections of the fatigue specimens were mechanically polished in the loading direction. Before testing, the specimens had a final polish in the loading direction in the gauge sections using 600-emery paper and 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.

Test Equipment and Procedure

Monotonic tension tests were performed to determine the yield strength, the tensile strength, the percent 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 electro-hydraulic 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 voltmeter. 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 3 Hz while in stress-controlled tests the frequency used was up to 75 Hz.

RESULTS

Chemical composition and microstructure Data

Figure 2 presents the ferrite pearlite microstructure of the 4140 induction through hardened steel. Figure 3 shows the inclusions observed in this material. The chemical composition as provided by the manufacturer is shown in Table 3.

Strain-Life Data

Constant amplitude test data obtained in this investigation are given in table 1. The stress amplitude corresponding to the strain amplitude was calculated from the peak load amplitude at the specimen half-life.

A fatigue strain life curve is shown in Figure 4, and is described by the following equation:

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma'_f}{E}(2N_f)^b + \varepsilon'_f(2N_f)^c \qquad \text{Eq 1}$$

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

The values of the strain-life parameters were determined from the best fit curve of the fatigue testing data including the true fracture stress and strain plotted at one reversal ($2N_f = 1$) and presented in table 2.

Cyclic Stress-Strain Curves

Stabilized, 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 cyclic stress-strain curve is described by the following equation:

$$\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{K'}\right)^{\frac{1}{n'}} \qquad \text{Eq 2}$$

where ε = True total strain amplitude

σ = Cyclically stable true stress amplitude

K' = Cyclic strength coefficient

n' = Cyclic strain hardening exponent

The constants K’ and n' obtained from a best fit of the above equation to the test data are given in table 2.

Mechanical Properties

The engineering monotonic tensile stress-strain curves are given in Figure 6. The true monotonic and true cyclic stress-strain curves plotted together are given in Figure 7. The monotonic properties along with the average hardness test results are included in table 2. The individual hardness measurements are given in Table 1.

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.

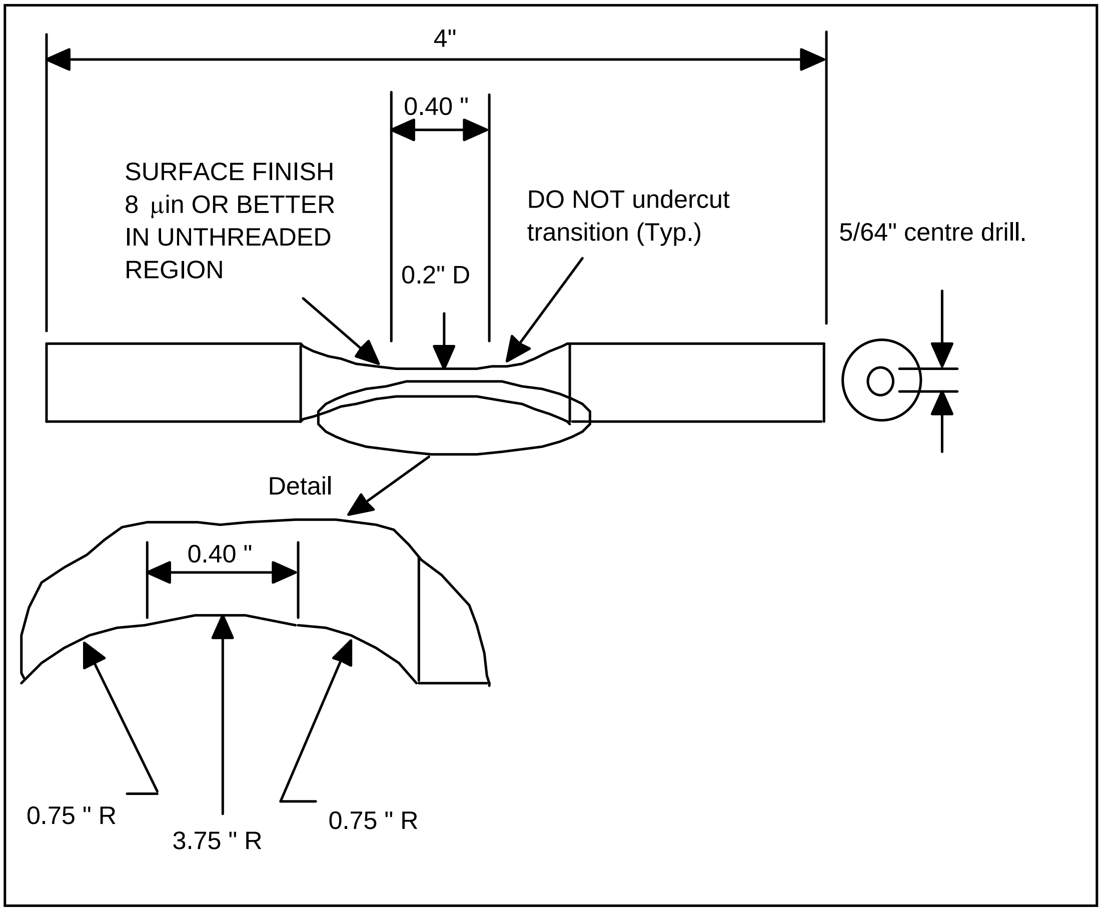

Figure 1 Smooth cylindrical fatigue specimen

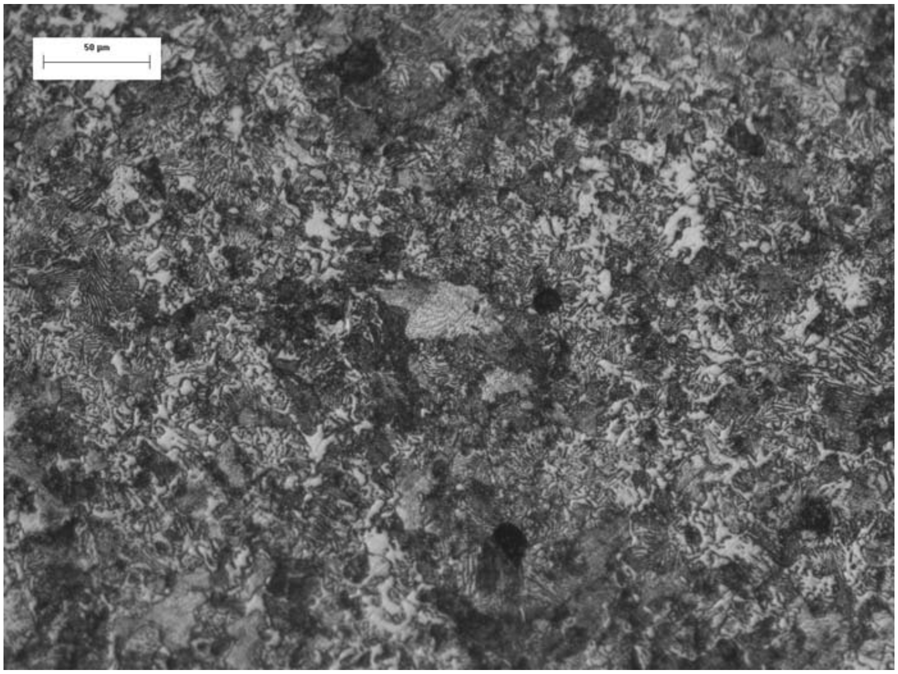

Figure 2 Photomicrographs of 4140 induction through hardened steel (X50)

Figure 3 Inclusions 4140 induction through hardened steel (X50)

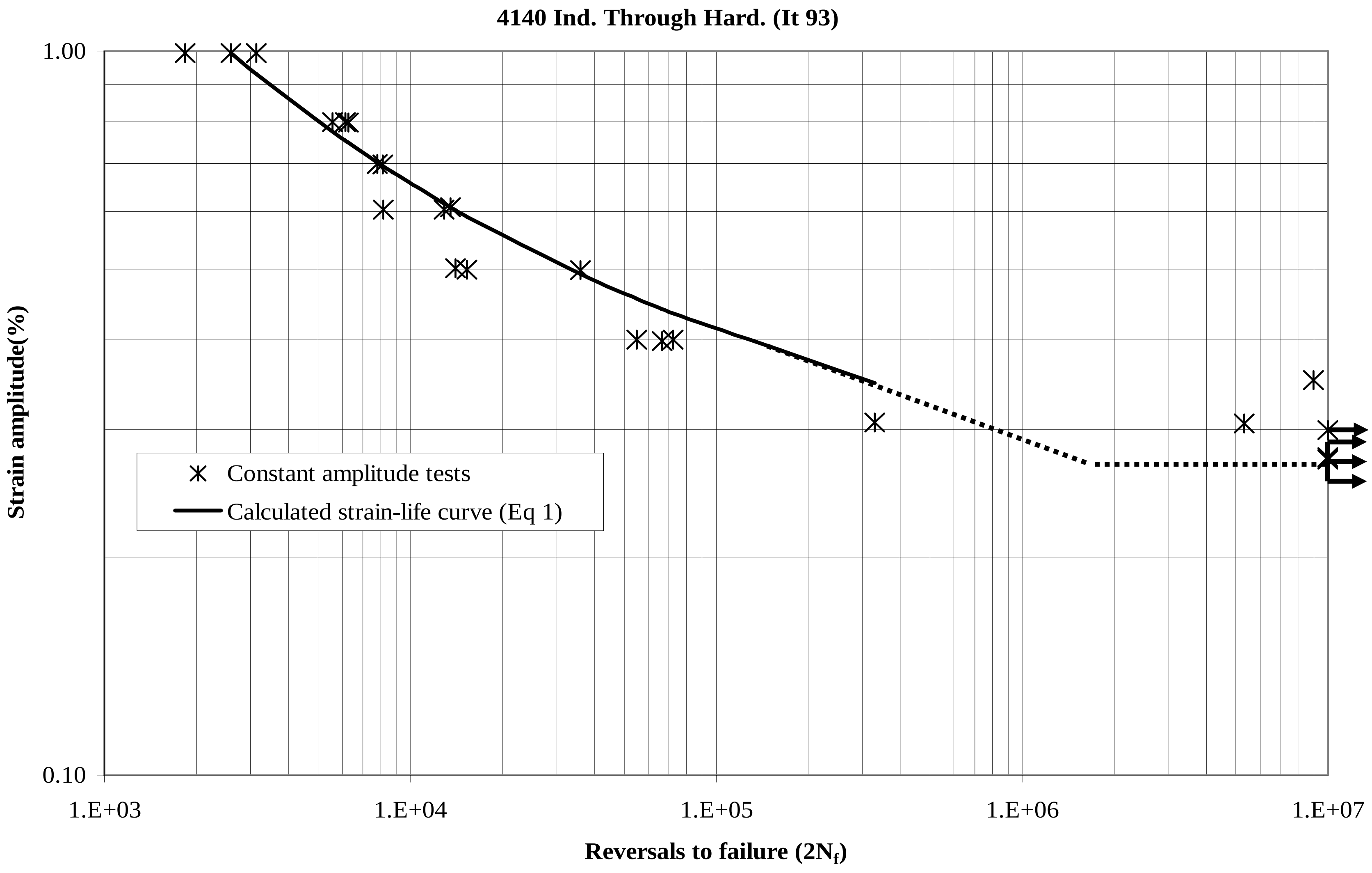

Figure 4. Constant amplitude fully reversed strain-life curve for Iteration 93

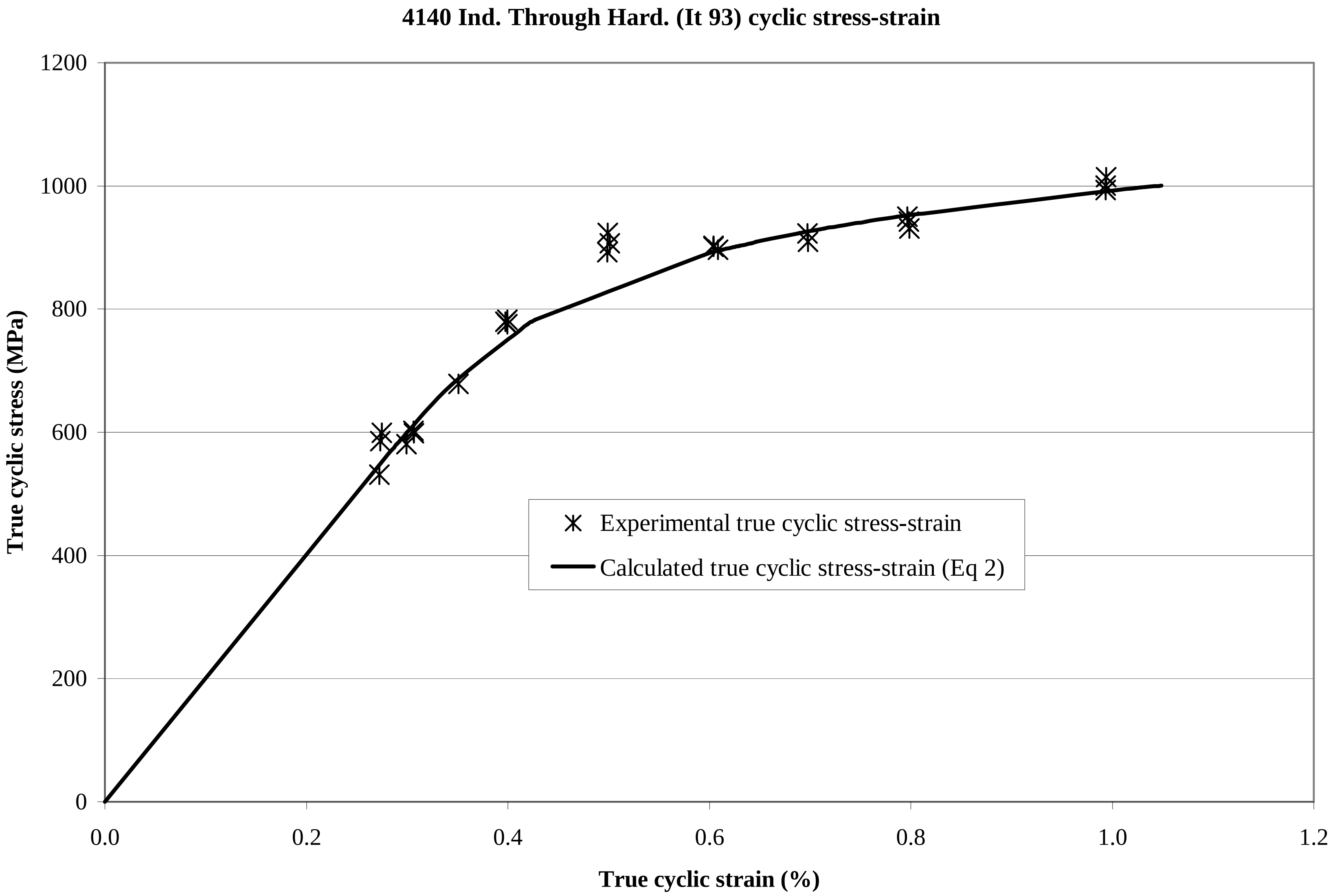

Figure 5. Cyclic true stress-strain curve for iteration 93

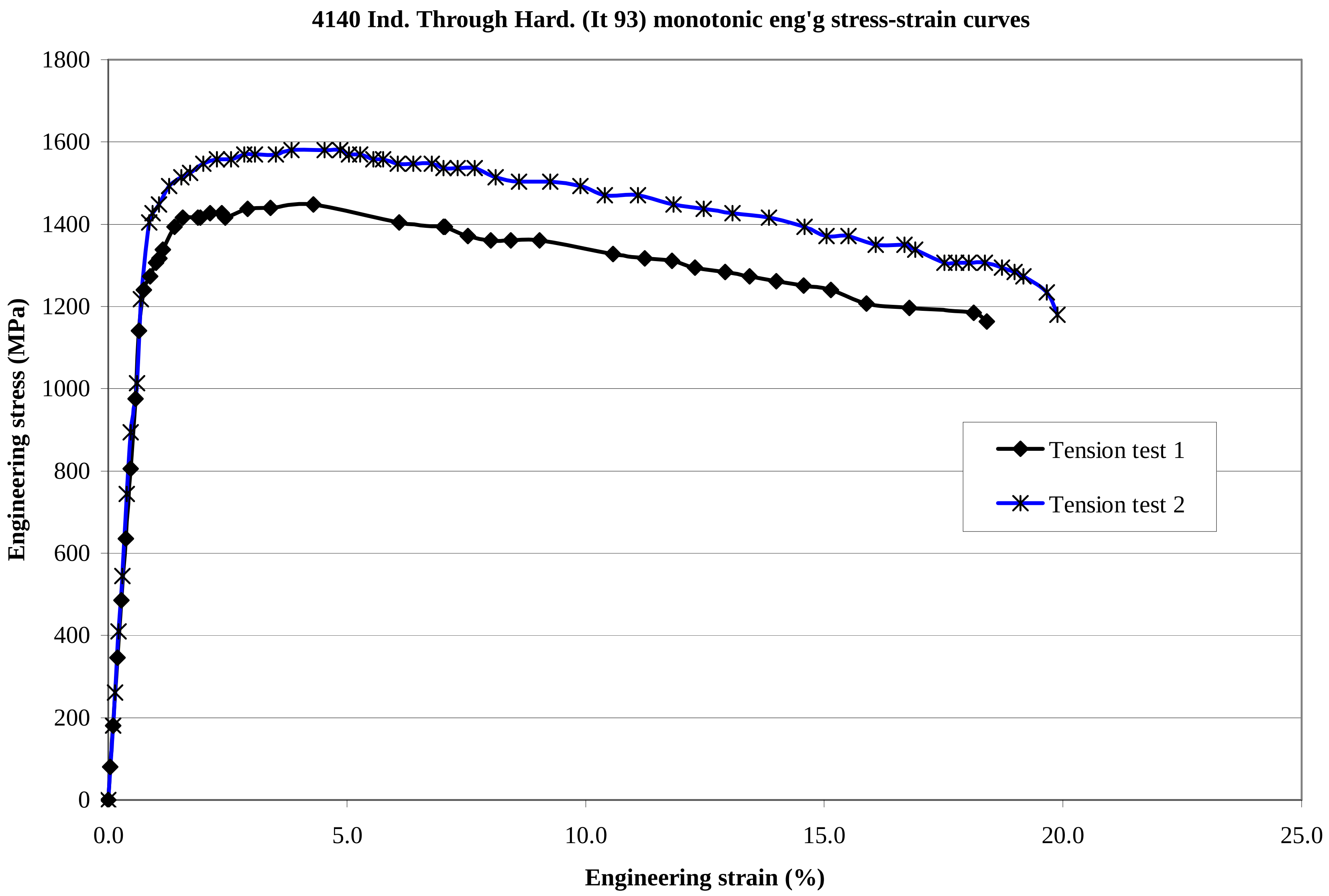

Figure 6. Tensile monotonic engineering stress-strain curves for iteration 93

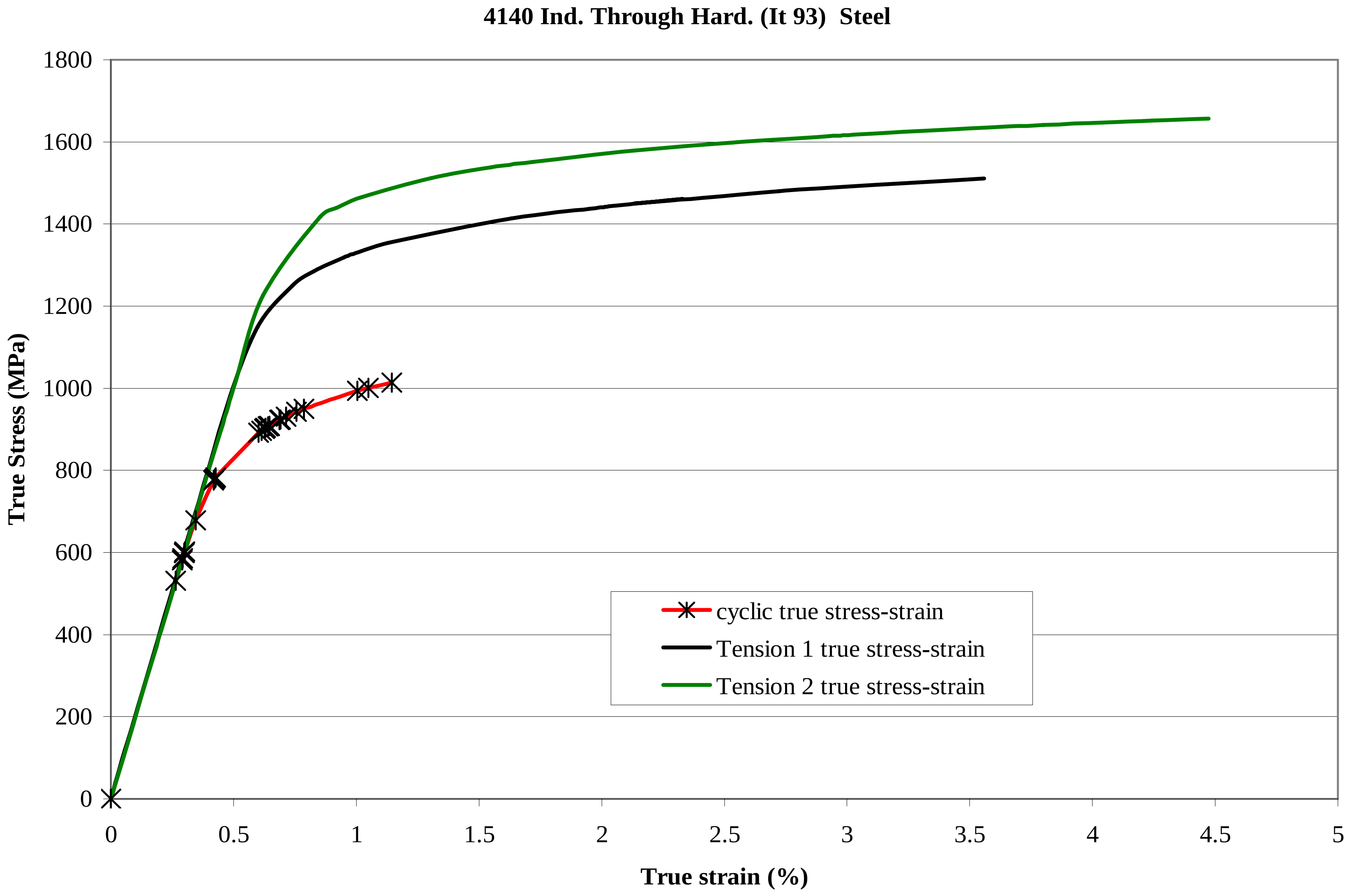

Figure 7. Monotonic and Cyclic true stress-strain curves for iteration 93

Table 1: Fatigue Data for Iteration 93

Sp#	Total Strain Amplitude (%)	Stress Amplitude (MPa)	Plastic Strain Amplitude (%)	Elastic Strain Amplitude (%)	(50% load drop) Fatigue Life (Reversals, 2Nf)	Hardness (Rockwell C)
17	0.993	993.3	0.500	0.493	3,142	
18	0.994	1014.1	0.490	0.504	1,834	
21	0.993	1000.2	0.497	0.497	2,588	
23	0.796	949.9	0.325	0.472	6,270	
24	0.798	942.1	0.330	0.468	5,562	
25	0.799	930.5	0.336	0.462	6,140	36.7
19	0.697	922.7	0.239	0.458	8,134	37.7
22	0.698	908.9	0.247	0.451	7,812	
12	0.604	901.4	0.157	0.448	8,166	39
13	0.609	896.5	0.163	0.445	13,510	
14	0.604	903.1	0.156	0.448	12,872	
2	0.501	907.1	0.051	0.450	14,070	
3	0.499	923.6	0.041	0.459	15,328	
15	0.498	892.2	0.055	0.443	36,012	
9	0.400	775.3	0.000	0.400	54,960	
10	0.397	779.5	0.000	0.397	66,680	
11	0.400	782.8	0.000	0.400	72,376	
26	0.351	678.6	0.000	0.351	8,962,288	
6	0.307	598.5	0.000	0.307	329,614	
7	0.300	580.6	0.000	0.300	10,000,000*	
8	0.306	602.6	0.000	0.306	5,336,566	
27	0.273	585.9	0.000	0.273	10,000,000*	
28	0.275	599.1	0.000	0.275	10,000,000*	
29	0.273	531.5	0.000	0.273	10,000,000*	

* Run out

Table 2: Monotonic and cyclic properties for iteration 93

Monotonic Properties	
Average Elastic Modulus, E (GPa)	201.4
Yield Strength (MPa)	1363
Ultimate tensile Strength (MPa)	1514
% Elongation (%)	19
% Reduction of Area (%)	48
True fracture strain, $Ln\ (A_i / A_f)$ (%)	65
True fracture stress, $\sigma_f = \frac{P_f}{A_f}$ (MPa)	2248
Bridgman correction $= \frac{P_f}{A_f} \Big/ \left(1+\frac{4R}{D_f}\right) Ln\left(1+\frac{D_f}{4R}\right)$ (MPa)	2071
Monotonic tensile strength coefficient, K (MPa)	1911
Monotonic tensile strain hardening exponent, n	0.055
Hardness, Rockwell C (HRC)	38
Cyclic Properties	
Cyclic Yield Strength, (0.2% offset)= $K'(0.002)^{n'}$ (MPa)	911
Cyclic strength coefficient, K' (MPa)	1613.7
Cyclic strain hardening exponent, n'	0.092
Fatigue Strength Coefficient, σ'_f (MPa)	2192
Fatigue Strength Exponent, b	-0.095
Fatigue Ductility Coefficient, ε'_f	0.7
Fatigue Ductility Exponent, c	-0.635

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

Table 3: Chemical composition for It 93

Element	**Weight (%)**
Carbon-- C	0.4100
Manganese (Mn)	0.9600
Phosphorus (P)	0.0090
Sulfur (S)	0.0090
Silicon (Si)	0.0000
Copper (Cu)	0.2000
Nickel (Ni)	0.1600
Chromium (Cr)	0.9900
Molybdenum (Mo)	0.2000
Tin (Sn)	0.0090
Aluminum (Al)	0.0310
Vanadium (V)	0.0030
Columbium/Niobium (Nb)	0.0020
Titanium (Ti)	0.0030
Boron (B)	0.0004
Calcium (Ca)	0.0003
Zirconium (Zr)	0.0010
Nitrogen (N)	0.0130
Oxygen (O)	0.0000
Cobalt (Co)	0.0080
Zinc (Zn)	0.0000
Lead (Pb)	0.0007
ASA	0.0060
Antimony (Sb)	0.0020
Tungsten (W)	0.0060