Fatigue Behavior and Monotonic Properties

For

AISI 9310 Steel

Iterations 127 &151

T.H. Topper and M. Yu

Department of Civil and Environmental Engineering

University of Waterloo

Waterloo, Ontario, Canada N2L 3G1

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

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Summary

The required mechanical fatigue properties, cyclic stress-strain data, strain-controlled fatigue data and overload fatigue data for AISI 9310 Steel 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. The Rockwell C hardness (RC) was determined as the average of nine measurements. Constant-amplitude tests as well as overload fatigue tests were conducted in laboratory air at room temperature to establish the cyclic stress-strain curve, strain-life curve.

Introduction

This report presents the results of tensile and fatigue tests performed on a group of 9310 Steel specimens (Iteration 127 and 151). The material was provided by the American Iron and Steel Institute. The objective of this investigation is to obtain the mechanical fatigue properties, cyclic stress-strain data, strain-life fatigue data, and overload data of this material.

Experimental Procedure

Specimen Preparation

The material for this study was received in the form of round bars. Smooth cylindrical fatigue specimens, shown in Figure 1, were machined from the cylindrical metal bars. Before testing, the specimens had a final polish in the loading direction in the gauge sections using 240, 400, 500, and 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

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 electro hydraulic testing machine.

A process control computer, controlled by FLEX software [1] was used to output constant strain amplitudes for constant strain amplitude tests and stress amplitudes for the overload tests.
Axial, constant strain amplitude, fully reversed (R=-1) strain-controlled fatigue tests were performed on smooth specimens. The stress-strain limits for 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 the tensile peak load from the peak load observed at one half the expected specimen life. The loading frequency varied from 0.05 Hz to 3 Hz. For fatigue lives greater than 100,000 reversals (once the stress-strain loops had stabilized) in constant amplitude tests and in periodic overload tests, the specimens were tested in load control. For the load-controlled tests, failure was defined as the separation of the smooth specimen into two pieces. The test frequencies used in this case were between 30 and 80 Hz.

Results

Chemical Composition

The chemical composition as provided by MacSteel is shown in Table 1.

Monotonic Tension Test

The engineering monotonic tensile stress-strain curve is given in Figure 2. The monotonic properties are given in Table 2. The Hardness of the 9310 Steel was taken as the average of the values obtained from three randomly chosen fatigue specimens and was given in Table 2

Cyclic Stress-Strain Curves

Stabilized stress data obtained from strain-life fatigue tests were used to construct the companion specimen cyclic stress-strain curve shown in Figure 3. The true monotonic and true cyclic stress-strain curves are plotted together in Figure 4. The cyclic stress-strain curve is described by the following equation:

$$\varepsilon = \frac{\sigma}{E_c} + \left(\frac{\sigma}{K^{'}}\right)^{\frac{1}{n^{'}}} \qquad \textbf{(Eq. 1)}$$

Where ε is the true total strain amplitude, σ is the cyclically stable true stress amplitude, E_c is the cyclic modulus of elasticity obtained from a best fit of the above equation to the test data and is given in Table 2, K’ is the cyclic strength coefficient , and n’ is the strain hardening exponent

Constant Amplitude Fatigue Data

Constant amplitude fatigue test data obtained in this investigation are given in Table 3. The stress amplitude corresponding to the peak strain amplitude was calculated from the peak load amplitude at one half of the specimen’s life. A constant amplitude fatigue life curve for 9310 Steel is given in Figure 5 and is described by the following equations:

$$\frac{\Delta\varepsilon_e}{2} = \frac{\sigma_f^1}{E}\left(2N_f\right)^b \qquad \textbf{(Eq. 2)}$$

$$\frac{\Delta\varepsilon_P}{2} = \varepsilon_f^1\left(2N\right)^C \qquad \textbf{(Eq. 3)}$$

Since $\Delta\varepsilon = \Delta\varepsilon_e + \Delta\varepsilon_P$ **(Eq. 4)**

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma'_f}{E}(2N_f)^b + \varepsilon'_f(2N_f)^c \qquad \textbf{(Eq. 5)}$$

Where;

$\frac{\Delta\varepsilon}{2}$ is the total strain amplitude,

$\frac{\Delta\varepsilon_e}{2}$ is the elastic strain amplitude $\left(\frac{\Delta\varepsilon_e}{2} = \frac{\Delta\varepsilon_{measured}}{2} - \frac{\Delta\varepsilon_p}{2}\right)$,

$\frac{\Delta\varepsilon_P}{2}$ is the plastic strain amplitude $\left(\frac{\Delta\varepsilon_p}{2} = \frac{\Delta\varepsilon_{measured}}{2} - \frac{\Delta\sigma_{measured}}{2E}\right)$,

$2N_f$ is the number of reversals to failure,

σ'_f is the fatigue strength coefficient,

b is the fatigue strength exponent,

ε'_f is the fatigue ductility coefficient,

c is the fatigue ductility exponent.

The values of the strain-life parameters were determined from a best fit of Equations 2 and 3 and are given in Table 2.

Overload Fatigue Test Data

Previous work at the University of Waterloo introduced an effective strain-life curve for use in fatigue damage calculations due to overloads [2]. This effective stain-life curve is derived from periodic overload tests consisting of two blocks of load cycles repeated. The first block consists of a single R=-1 overload (tensile and compressive overload peaks) cycle, and this is followed by a block of smaller load cycles that have the same tensile peak stress as the overload cycle. The minimum of the small cycles varies from test to test, and similarly the number of small cycles between the overload cycles is varied depending upon the expected life. These two blocks are then repeated until the specimen fails. The aim is to have the large cycle (overload cycle) occur frequently enough that the crack opening stress remains below the minimum stress of the smaller cycles and crack growth during the application of the small cycles is free of crack closure. The overload cycle amplitude used in this testing was set equal to the fully reversed constant-amplitude stress level that would give a fatigue life of 10,000 cycles. The reason for this choice was to achieve a large reduction in crack opening stress without allotting an undue fraction of the total damage to the large cycles. The number of small cycles in the second block was chosen so that they did 80 to 90% of the damage to the specimen and that they were free from closure. The damage due to the overloads was removed using Miner's rule [3] and the equivalent failure life of the small cycles in each test was calculated. The overload fatigue data are given in Table 4. The equivalent strain-life fatigue curve is shown together with constant amplitude fatigue life curve in Figure 6.

Microstructure:

Microstructure was analyzed by Chrysler lab, as shown in Figure 7 and 8.

References

[1] M. Pompetzki, R. Saper, T. Topper, Software for rig frequency control of variable amplitude fatigue tests, Canadian Metallurgical Quarterly 25 (2) (1987) 181-194

[2] T. Topper, T. Lam, Effective strain-fatigue life data for variable amplitude loading, International Journal of Fatigue 19 (1) (1997) 137-143

[3] I. Stephens, Metal Fatigue in Engineering, Second edition, John Wiley & Sons, 2001

Note:

Some specimen IDs, a digital number with a letter "B", such as 10B, it means this specimen (10) was tested at low strain amplitude without failure, then it was tested at high strain amplitude (10B).

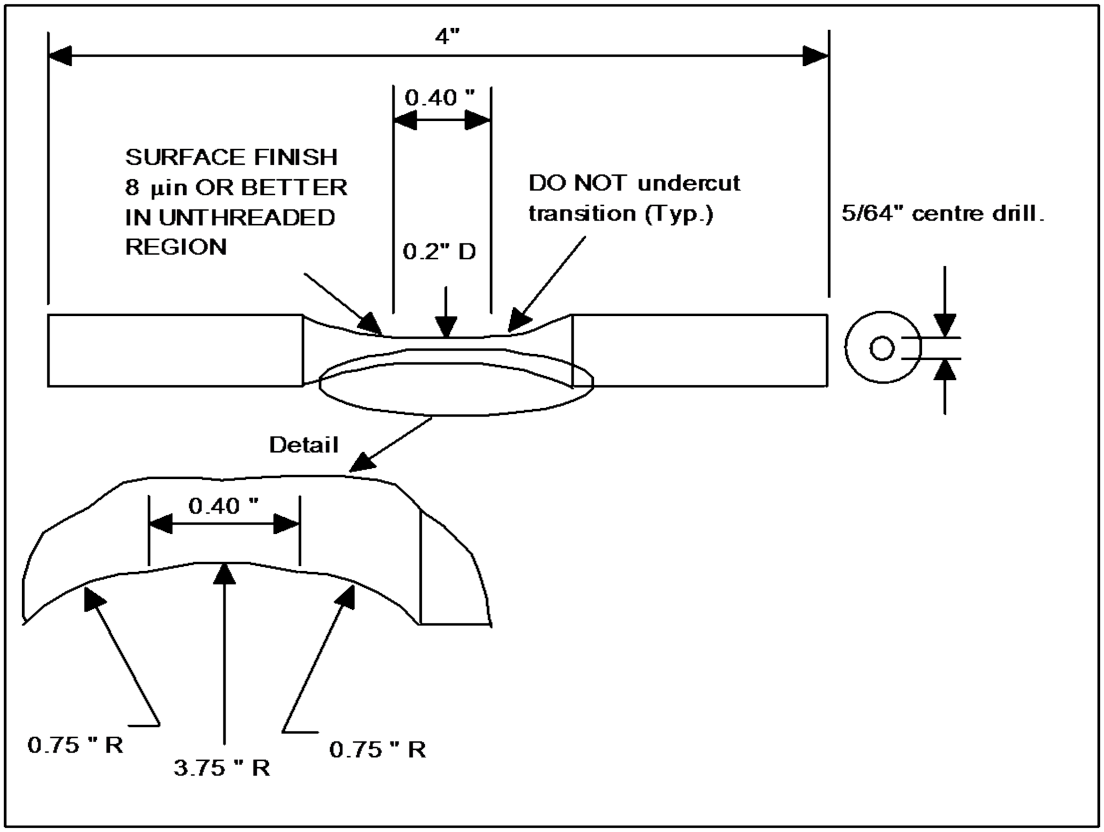

Figure 1: Uni-axial smooth cylindrical fatigue specimen

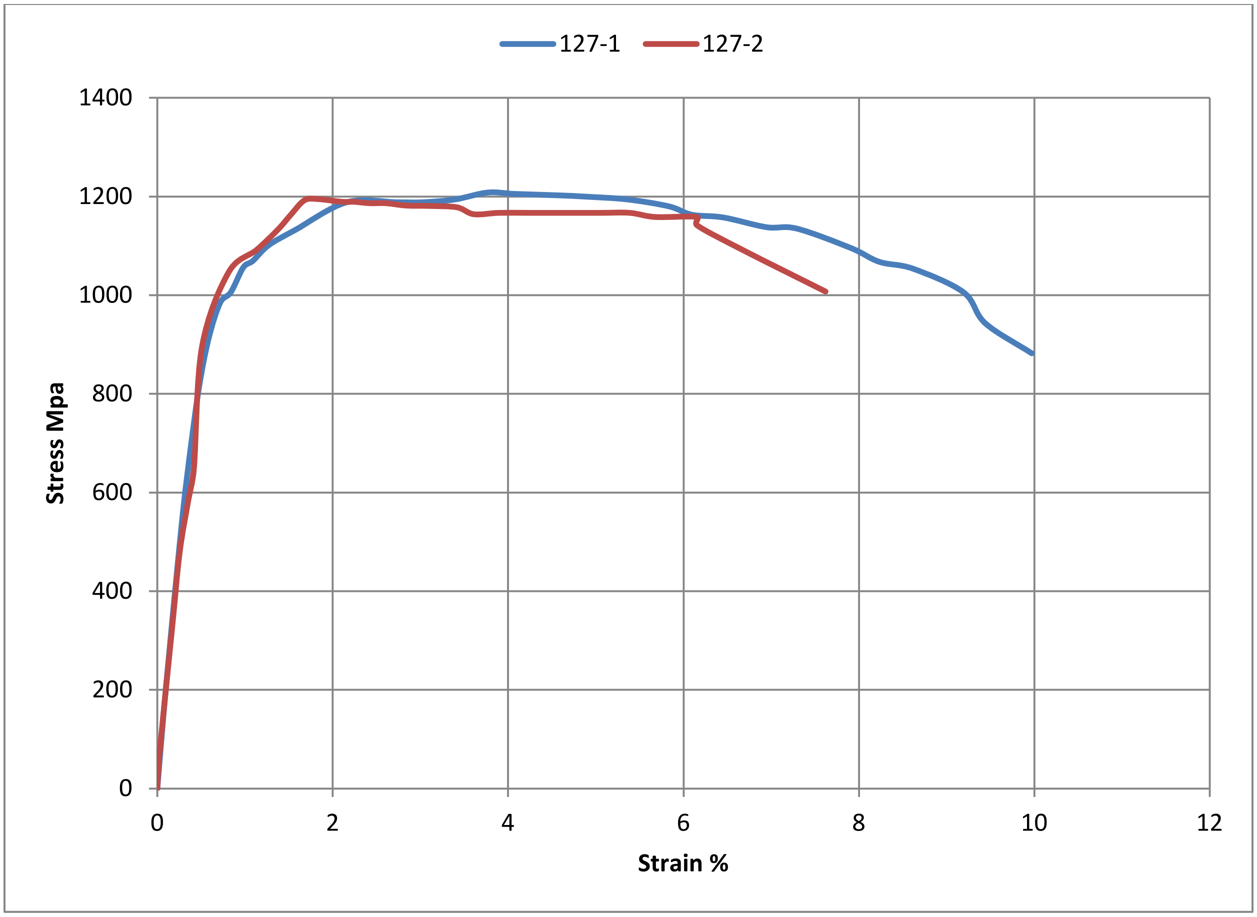

Figure 2: Monotonic engineering stress-strain curves for AISI 9310 (IT 127)

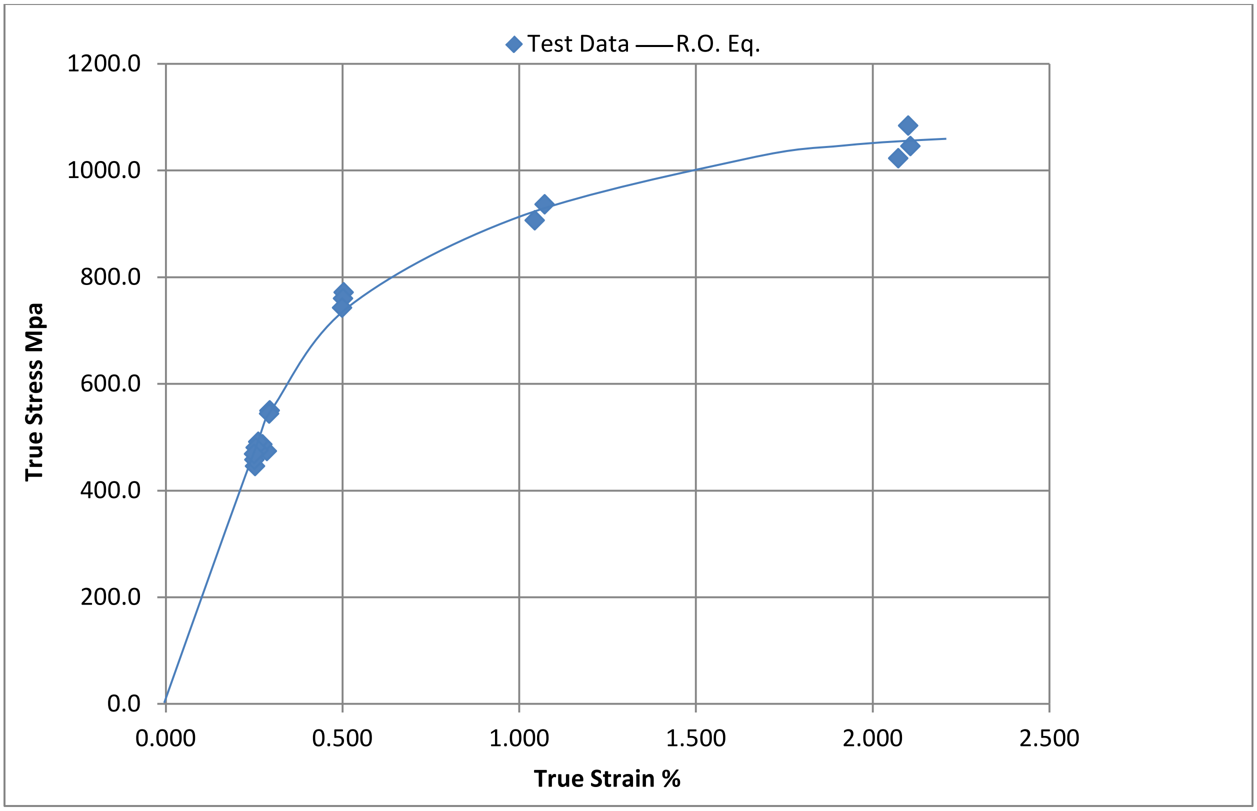

Figure 3: Cyclic true stress-strain curve for AISI 9310 (IT 127)

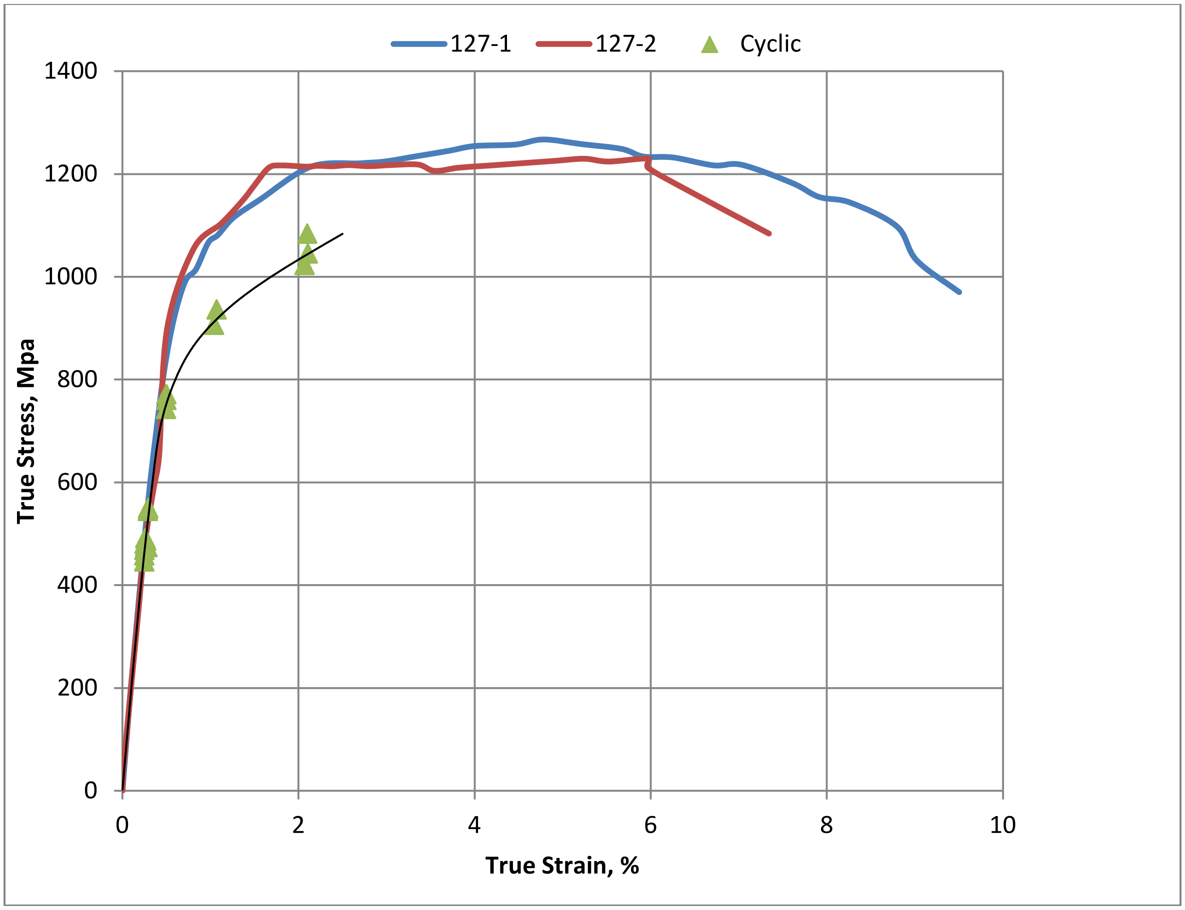

Figure 4: Monotonic & cyclic true stress-strain curves for AISI 9310 Steel (IT 127)

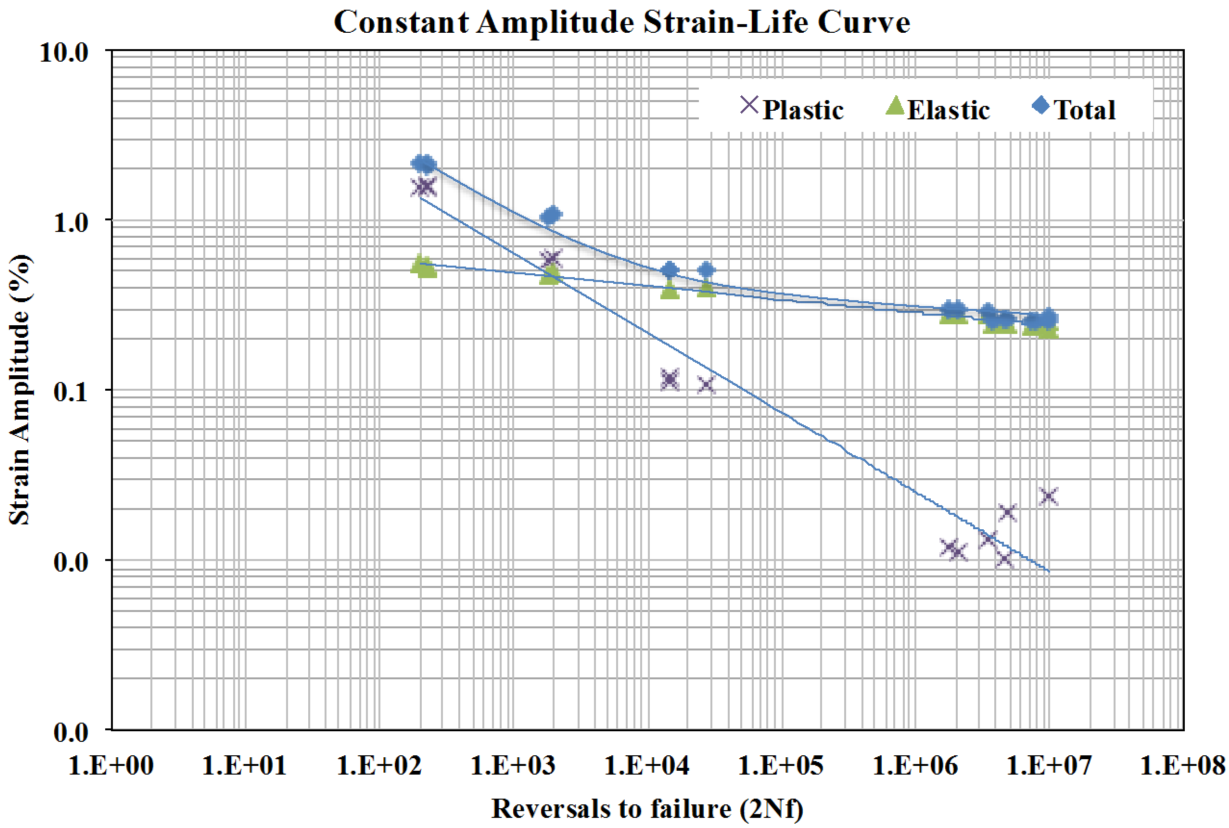

Figure 5: Strain-life fatigue curves for AISI 9310 (IT 127)

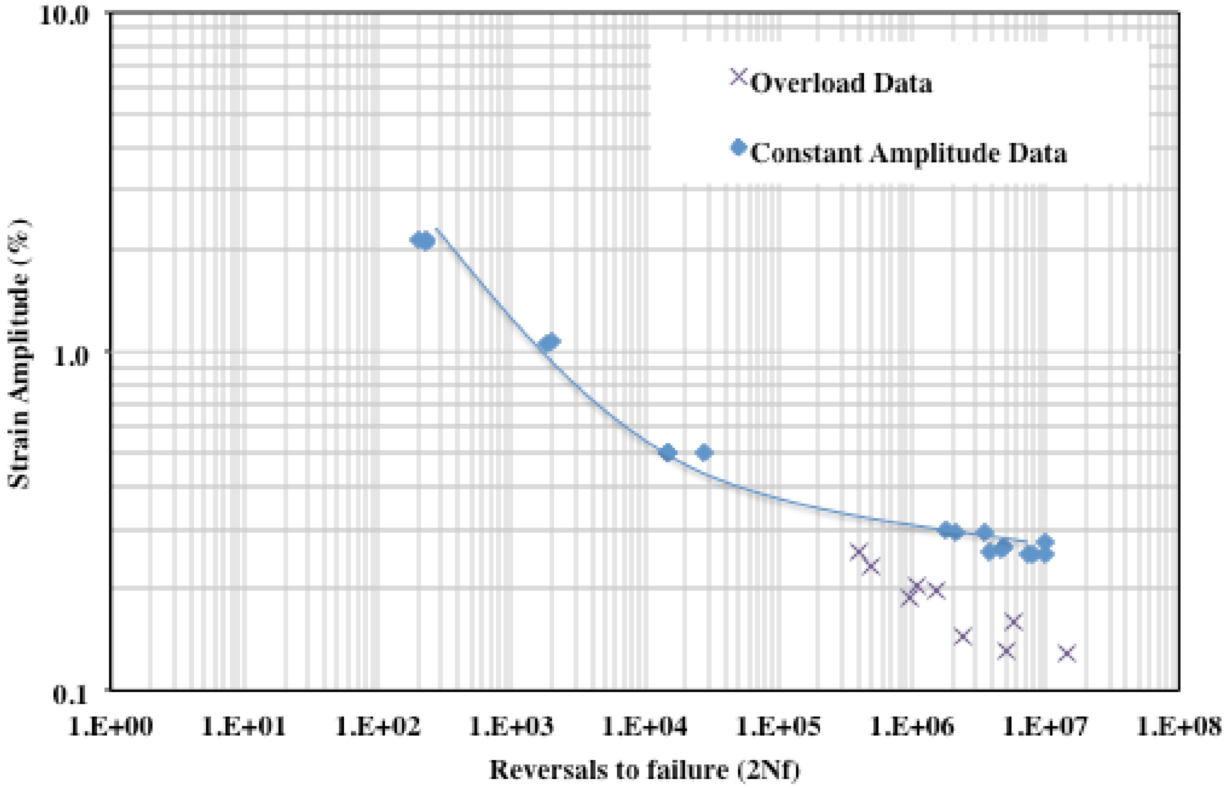

Figure 6: Overload and constant fatigue curves for AISI 9310 (IT 127)

Figure 7: Microstructure of Iteration 127/151, low magnification.

Figure 8: Microstructure of Iteration 127/151, high magnification

Table 1: Chemical Analysis (Bar Average) for AISI 9310 Steel (Iterations 127 and 151)

C	0.13
Mn	0.47
P	0.008
S	0.005
Si	0.22
Ni	3.08
Cr	1.1
Mo	0.09
Cu	0.18
Sn	0.012
Al	0.018
V	0.004
Cb	0.003
N	0.0102

Table 2: Monotonic and Cyclic Properties for AISI 9310 Steel (IT 127 and 151)

Monotonic Properties	
Average elastic modulus, E (GPa)	194.5
Yield strength (MPa)	990
Ultimate tensile strength (MPa)	1201
% Elongation (%)	8.8%
% Reduction of area (%)	56.5%
True fracture strain, $Ln\ (A_i / A_f)$ (%)	83.2%
True fracture stress, $\sigma_f = \frac{P_f}{A_f}$ (MPa)	2172
Monotonic tensile strength coefficient, K (MPa)	1796
Monotonic tensile strain hardening exponent, n	0.0937
Hardness, Rockwell C (HRC)	37.9
Cyclic Properties	
Cyclic Yield Strength, (0.2% offset) $= K'(0.002)^{n'}$ (MPa)	798
Cyclic strength coefficient, K' (MPa)	1778
Cyclic strain hardening exponent, n'	0.129
Cyclic elastic modulus, E_c (GPa)	194.5
Fatigue strength coefficient, $\square'_f$ (MPa)	1606
Fatigue strength exponent, b	-0.076
Fatigue ductility coefficient, $\square'_f$	0.275
Fatigue ductility exponent, c	-0.53

Table 3: Constant Strain Amplitude Data for AISI 9310 Steel (IT 127)

Sp#	Total Strain Amplitude (%)	Stress Amplitude (MPa)	Plastic Strain Amplitude (%)	Elastic Strain Amplitude (%)	(50% load drop) Fatigue Life (Reversals, 2Nf)	Hardness (Rockwell HRC)
10B	2.130	1023.6	1.570	0.537	230	Hardness HRC Average of nine readings 37.9
9	2.124	1061.1	1.544	0.557	204	
26	2.095	1001.9	1.547	0.526	230	
8	1.079	926.4	0.591	0.481	1,994	
23	1.050	897.2	0.578	0.466	1,872	
6	0.505	767.3	0.108	0.396	27,266	
25	0.503	756.2	0.111	0.391	15,000	
27	0.501	738.9	0.118	0.382	14,668	
4	0.296	548.4	0.012	0.283	1,829,456	
5	0.294	547.7	0.011	0.282	2,144,144	
3	0.293	542.4	0.013	0.280	3,513,540	
10	0.274	485.2	0.024	0.250	10,000,000	
22	0.264	474.2	0.019	0.244	4,882,916	
7	0.263	490.0	0.010	0.253	4,726,222	
14	0.256	479.4	0.008	0.247	3,774,562	
15	0.254	458.7	0.024	0.229	10,000,000	
18	0.252	456.4	0.016	0.235	7,408,730	
24	0.251	467.2	0.010	0.241	7,969,424	

Table 4: Overload Data for AISI 9310 Steel (IT 151)

SP#	Stress Amplitude for small cycles (MPa)	Strain Amplitude for small cycles (%)	Number of cycles between overloads	Total number of cycles to failure	Equivalent fatigue life	
					(Cycles-Nf)	(Reversals-2Nf)
17	503	0.259	100	169,661	202,316	404,632
12	449	0.231	200	219,291	245,079	490,158
16	397	0.204	300	457,219	537,692	1,075,384
11	387	0.199	300	605,612	756,381	1,512,762
21	368	0.189	400	429,872	480,498	960,996
19	309	0.159	750	2,057,740	2,832,522	5,665,044
28	279	0.144	1,250	1,100,880	1,206,403	2,412,806
20	253	0.13	1,250	2,110,437	2,537,298	5,074,596
29	251	0.129	1,250	5,374,296	7,346,291	14,692,582