Fatigue Behavior and Monotonic Properties

For

AISI 4320 Steel

Iterations 123 &147

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Prepared for:
The SMDI Bar Steel Applications Group
February, 2011

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Summary

The required mechanical fatigue properties, cyclic stress-strain data, strain-controlled fatigue data and overload fatigue data for AISI 4320 Steel (IT 123 and 147) 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 as well as the effective strain-life curve.

Introduction

This report presents the results of tensile and fatigue tests performed on a group of 4320 Steel specimens (Iteration 123 and 147). 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 50 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 4320 Steel was taken as the average of the values obtained from three randomly chosen fatigue specimens and is 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 4320 Steel is given in Figure 5 and is described by the following equations:

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

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

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

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma_f'}{E}(2N_f)^b \quad + \varepsilon_f'(2N_f)^c$$ **(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 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 for iteration 146 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 for iteration 146 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 21B, it means this specimen (21) was tested at low strain amplitude without failure, then it was tested at high strain amplitude (21B).

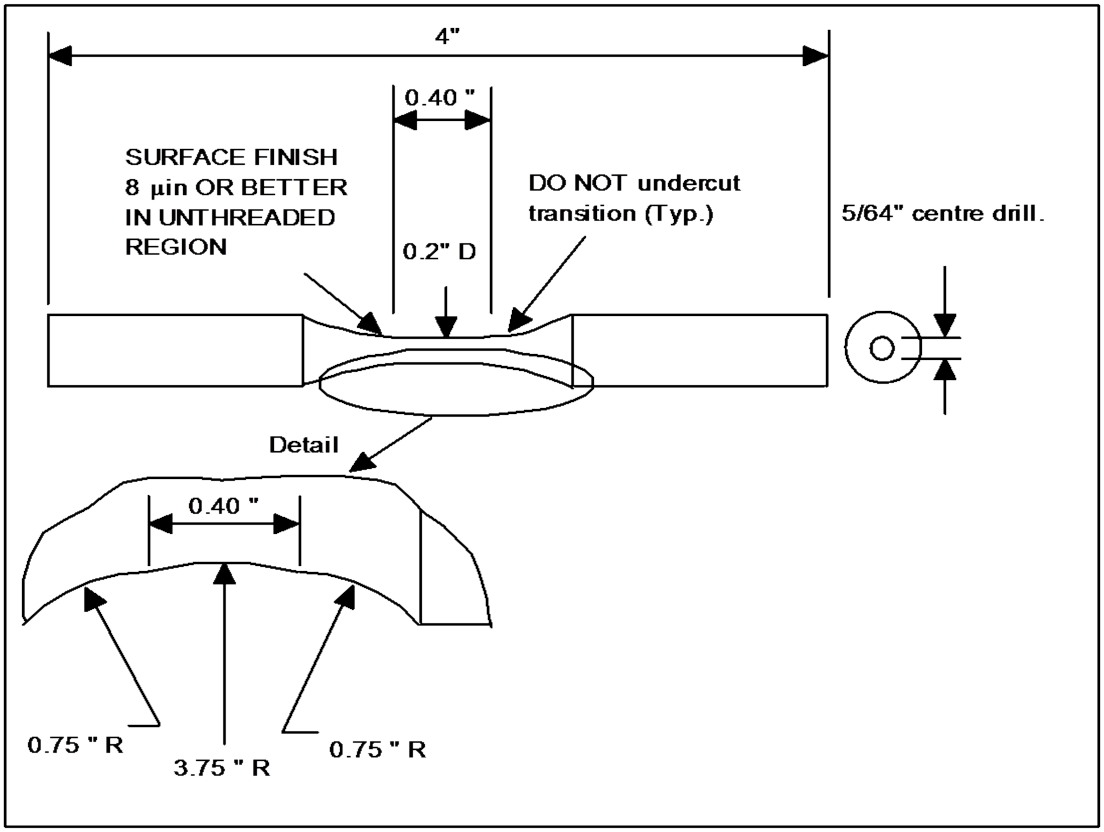

Figure 1: Uni-axial smooth cylindrical fatigue specimen

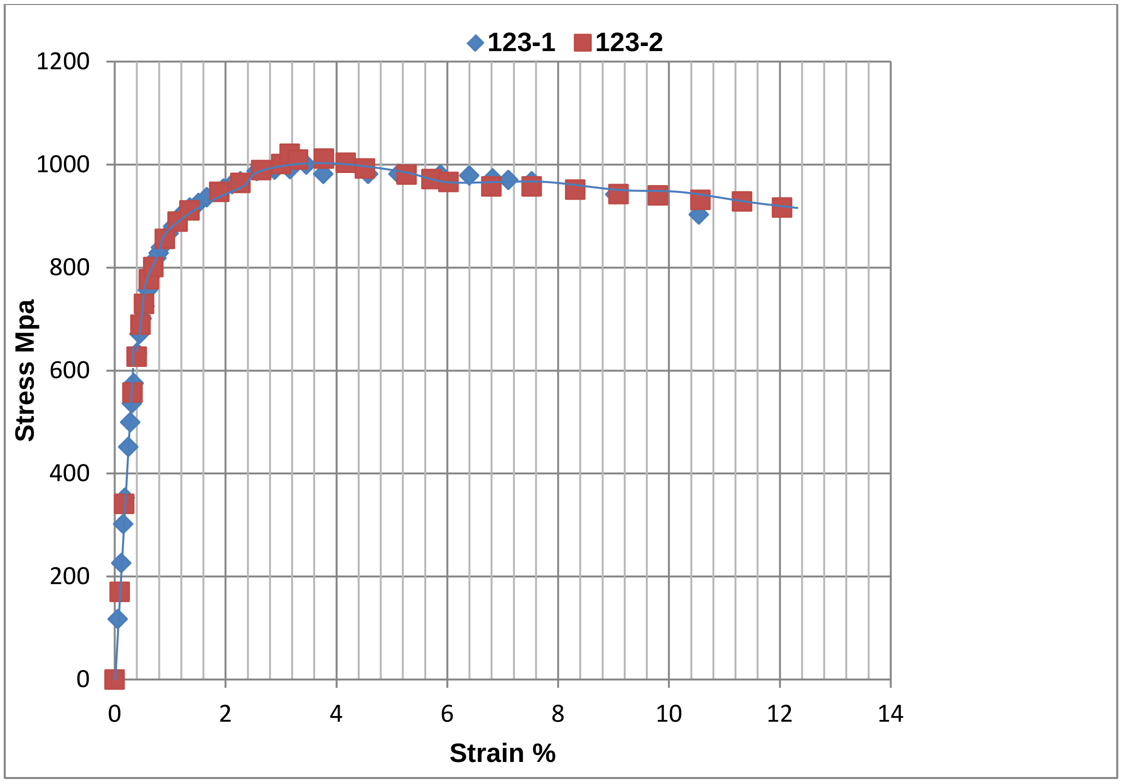

Figure 2. Monotonic engineering stress-strain curves for AISI 4320 (IT 123)

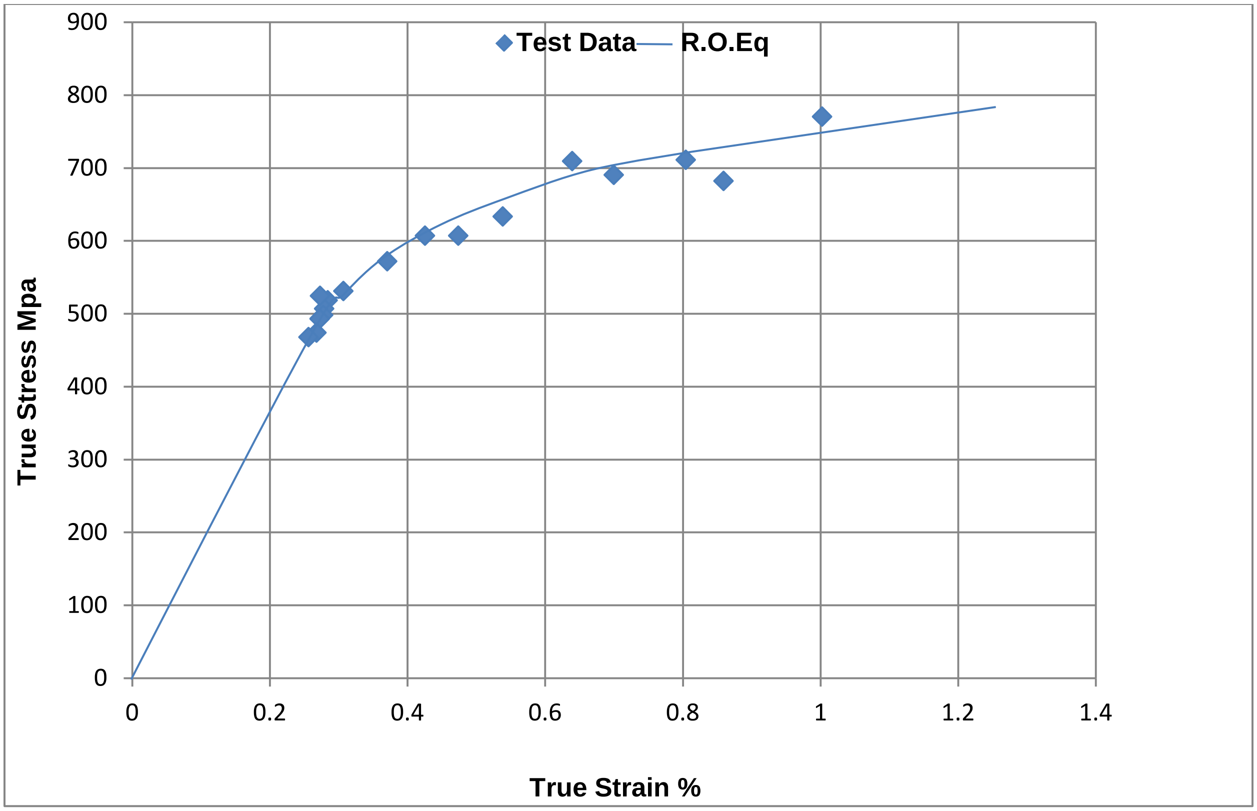

Figure 3 Cyclic true stress-strain curve for AISI 4320 (IT 123)

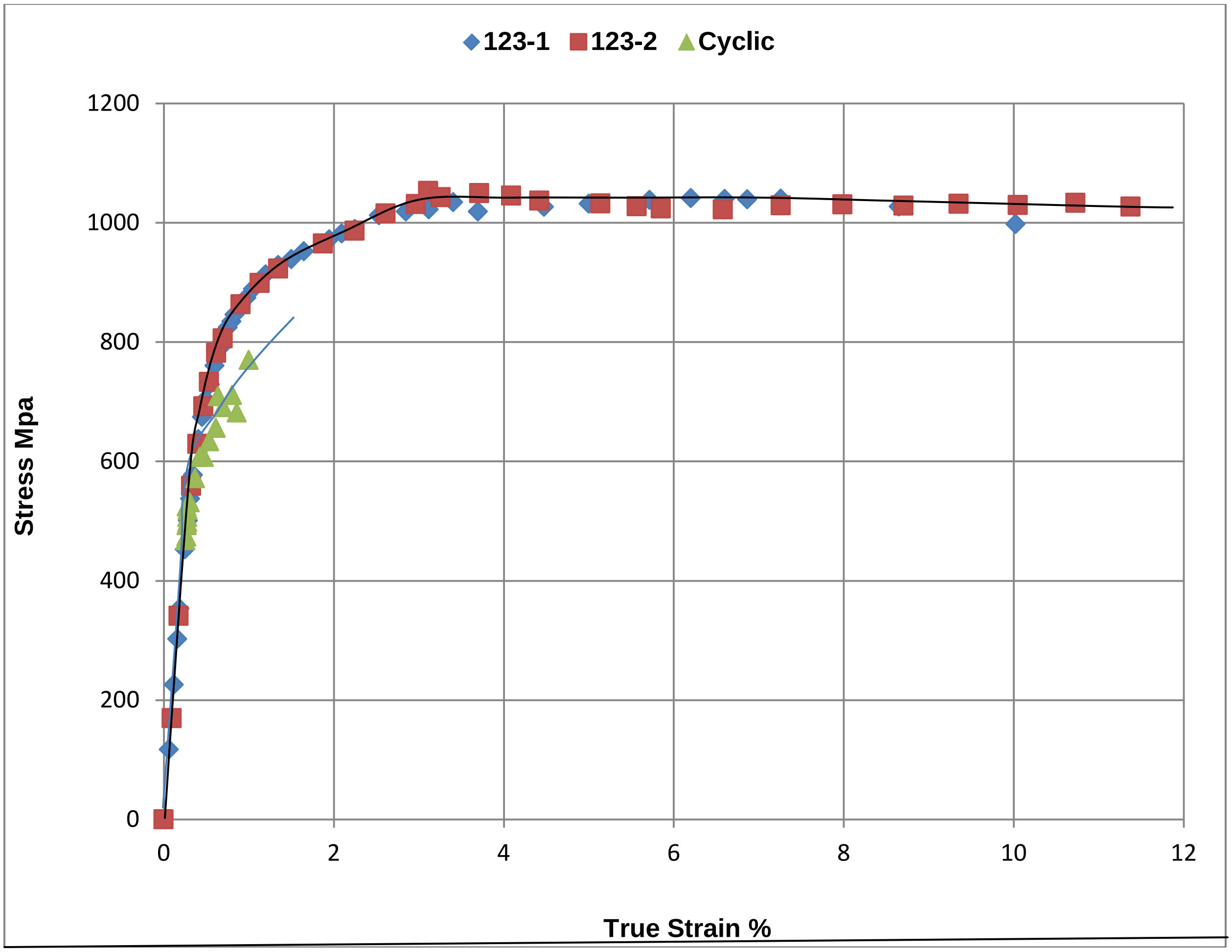

Figure 4: Monotonic & cyclic true stress-strain curves for AISI 4320 Steel (IT 123)

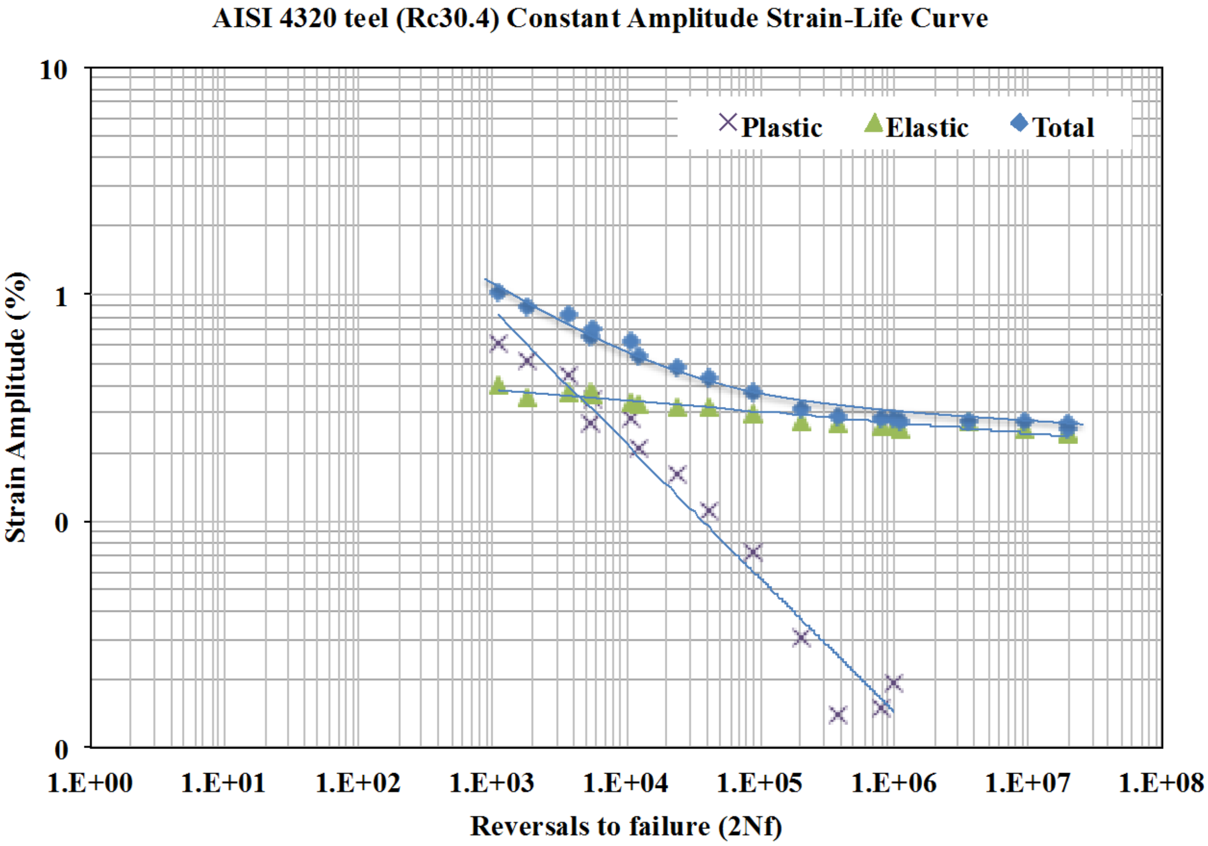

Figure 5: Strain-life curves for AISI 4320 (IT 123)

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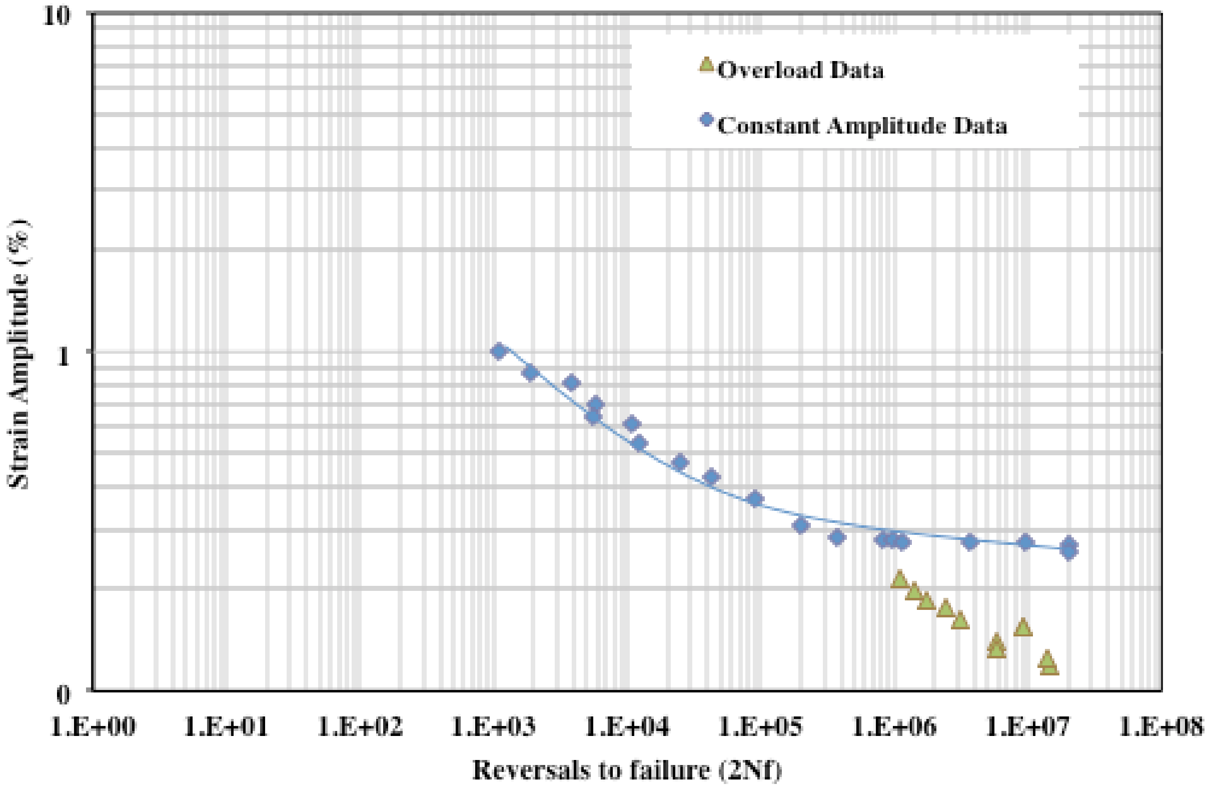

Figure 6: Overload and constant fatigue curves for AISI 4320 (IT 123)

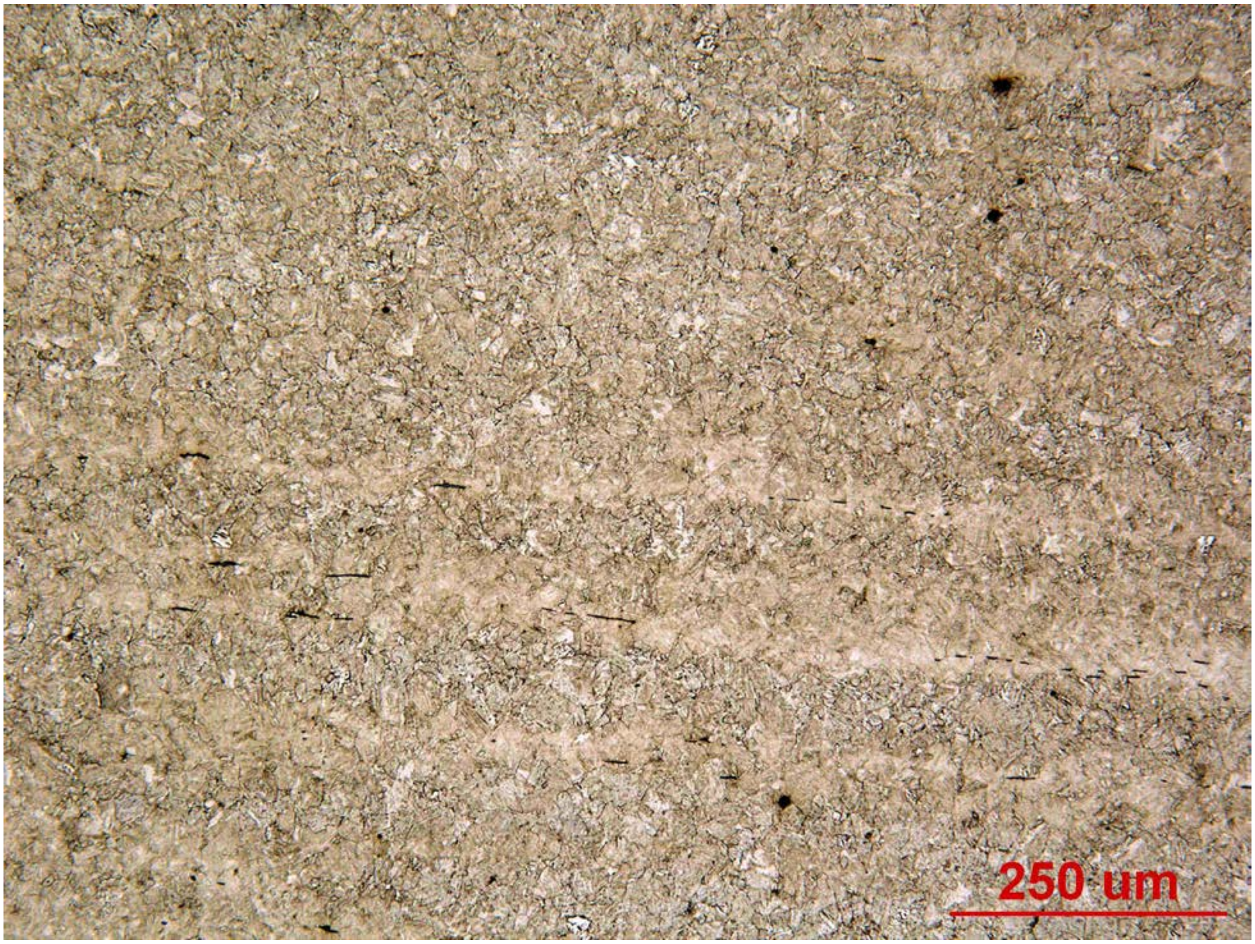

Figure 7: Microstructure of Iteration 123/147, low magnification

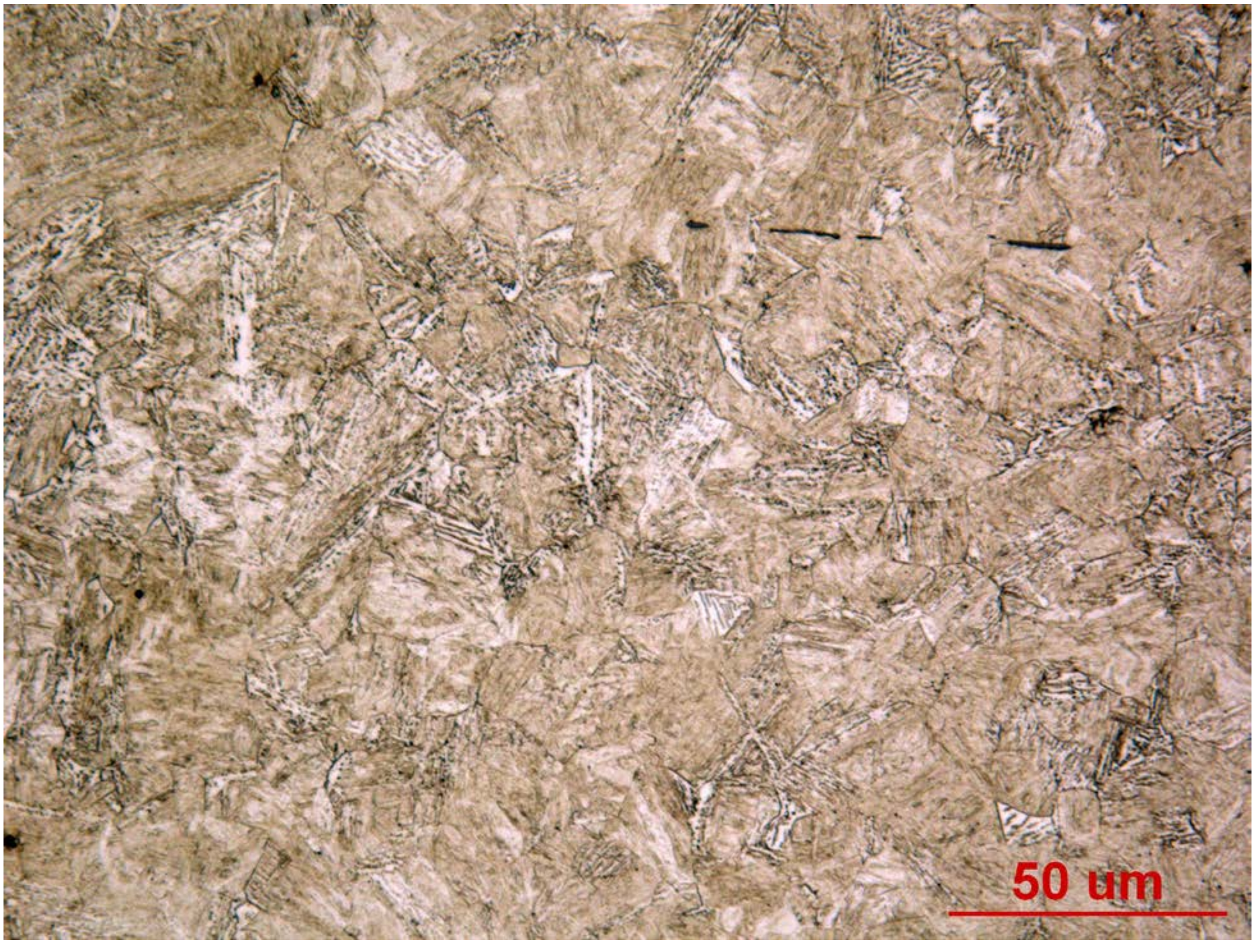

Figure 8: Microstructure of Iteration 123/147, high magnification

Table 1: Chemical Analysis (Bar Average) for AISI 4320 Steel (Iterations 123 and 147)

C	0.19
Mn	0.62
P	0.007
S	0.025
Si	0.24
Ni	1.76
Cr	0.5
Mo	0.25
Cu	0.16
Sn	0.007
Al	0.02
V	0.004

Table 2: Monotonic and Cyclic Properties for AISI 4320 Steel
(IT 123and 147)

Monotonic Properties	
Average elastic modulus, E (GPa)	194.3
Yield strength (MPa)	745
Ultimate tensile strength (MPa)	1010
% Elongation (%)	11.3%
% Reduction of area (%)	57%
True fracture strain, $Ln\ (A_i / A_f)$ (%)	84.6%
True fracture stress, $\sigma_f = \frac{P_f}{A_f}$ (MPa)	1984
Monotonic tensile strength coefficient, K (MPa)	1219
Monotonic tensile strain hardening exponent, n	0.058
Hardness, Rockwell C (HRC)	30.4
Cyclic Properties	
Cyclic Yield Strength, (0.2% offset) $= K'(0.002)^{n'}$ (MPa)	643
Cyclic strength coefficient, K' (MPa)	1399
Cyclic strain hardening exponent, n'	0.125
Cyclic elastic modulus, E_c (GPa)	194.3
Fatigue strength coefficient, $\square_f$ (MPa)	1215
Fatigue strength exponent, b	-0.066
Fatigue ductility coefficient, $\square_f$	0.238
Fatigue ductility exponent, c	-0.5

Table 3: Constant Strain Amplitude Data for AISI 4320 Steel (IT 123)

Sp#	Total Strain Amplitude (%)	Stress Amplitude (MPa)	Plastic Strain Amplitude (%)	Elastic Strain Amplitude (%)	(50% load drop) Fatigue Life (Reversals, 2Nf)	Hardness (Rockwell C)
3	1.008	763	0.602	0.401	1,106	Average Hardness HRC 30.4
10	0.863	676	0.504	0.355	1,878	
21B	0.808	706	0.434	0.370	3,764	
24	0.703	686	0.340	0.360	5,700	
9B	0.642	705	0.270	0.369	5,508	
22	0.617	641	0.278	0.336	10,880	
7	0.540	630	0.209	0.330	12,500	
27	0.475	604	0.158	0.316	24,948	
23	0.427	605	0.109	0.316	42,760	
26	0.371	570	0.073	0.298	89,462	
4	0.308	529	0.031	0.277	201,438	
14	0.285	517	0.014	0.270	377,226	
28	0.280	505	0.015	0.264	818,692	
20	0.278	497	0.019	0.259	985,868	
29	0.274	523	0.000	0.273	3,608,952	
15	0.273	492	0.016	0.257	9,639,036	
18	0.273	492	0.016	0.257	1,124,582	
21	0.269	473	0.021	0.247	20,000,000	
9	0.257	466	0.013	0.244	20,000,000	

Table 4: Periodic Overload Data for AISI 4320 Steel (IT 147)

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)
8	312	0.162	50	380,889	1,567,703	3,135,406
6	227	0.118	1,000	4,255,331	7,400,897	14,801,794
13	241	0.125	2,000	5,232,332	7,083,455	14,166,910
17	340	0.177	50	358,173	1,237,690	2,475,380
19	269	0.14	1,000	2,225,223	2,859,528	5,719,056
5	297	0.155	500	2,379,455	4,531,861	9,063,722
25	255	0.133	2,000	2,515,257	2,876,099	5,752,198
12	354	0.184	100	466,115	864,468	1,728,936
11	382	0.199	400	601,901	706,846	1,413,692
16	411	0.214	200	438,381	558,714	1,117,428
30	297	0.155	500	2,400,291	4,608,482	9,216,964