



# **Fatigue Behavior and Monotonic Properties**

**For**

**AISI 9310 Steel**

**Iterations 125 &149**

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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 as well as the effective strain-life curve.

## **Introduction**

This report presents the results of tensile and fatigue tests performed on a group of 9310 Steel specimens (Iteration 125 and 149). 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°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 50 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 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:

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

Where  $\varepsilon$  is the true total strain amplitude,  $\sigma$  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:

$$\frac{\Delta\varepsilon_e}{2} = \frac{\sigma_f^1}{E} (2N_f)^b \quad (\text{Eq. 2})$$

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon_f^1 (2N)^c \quad (\text{Eq. 3})$$

$$\text{Since } \Delta\varepsilon = \Delta\varepsilon_e + \Delta\varepsilon_p \quad (\text{Eq. 4})$$

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

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,

$\sigma'_f$  is the fatigue strength coefficient,

$b$  is the fatigue strength exponent,

$\varepsilon'_f$  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 strain-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 12B, it means this specimen (12) was tested at low strain amplitude without failure, then it was tested at high strain amplitude (12B).

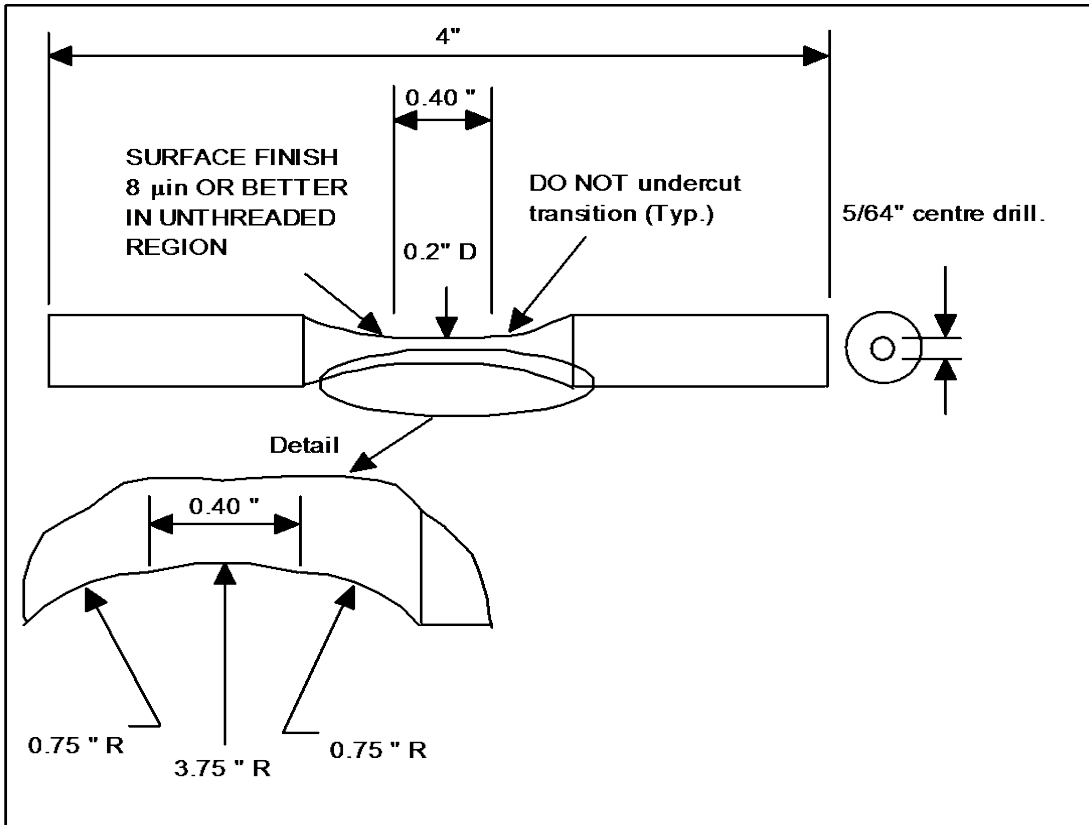


Figure 1: Uni-axial smooth cylindrical fatigue specimen

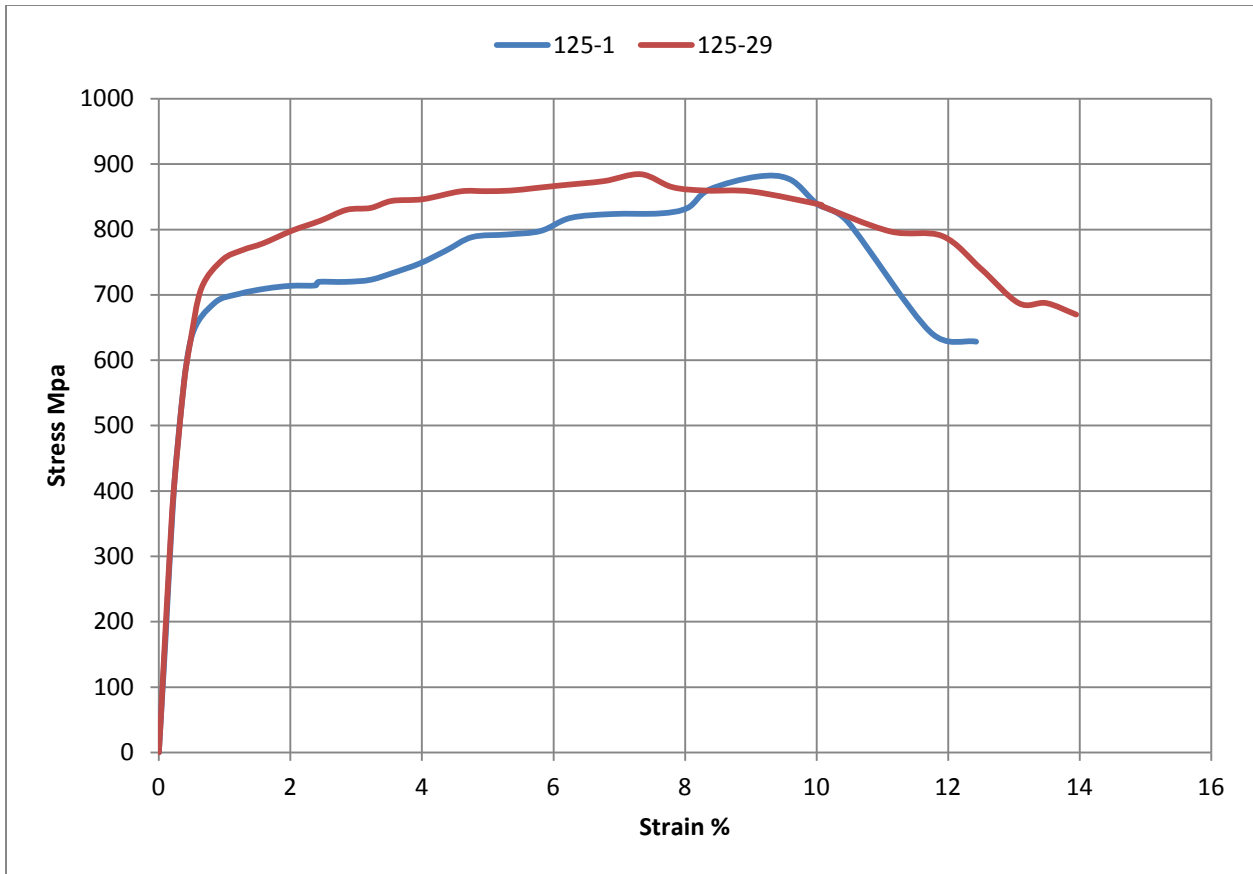


Figure 2: Monotonic engineering stress-strain curves for AISI 9310 (IT 125)

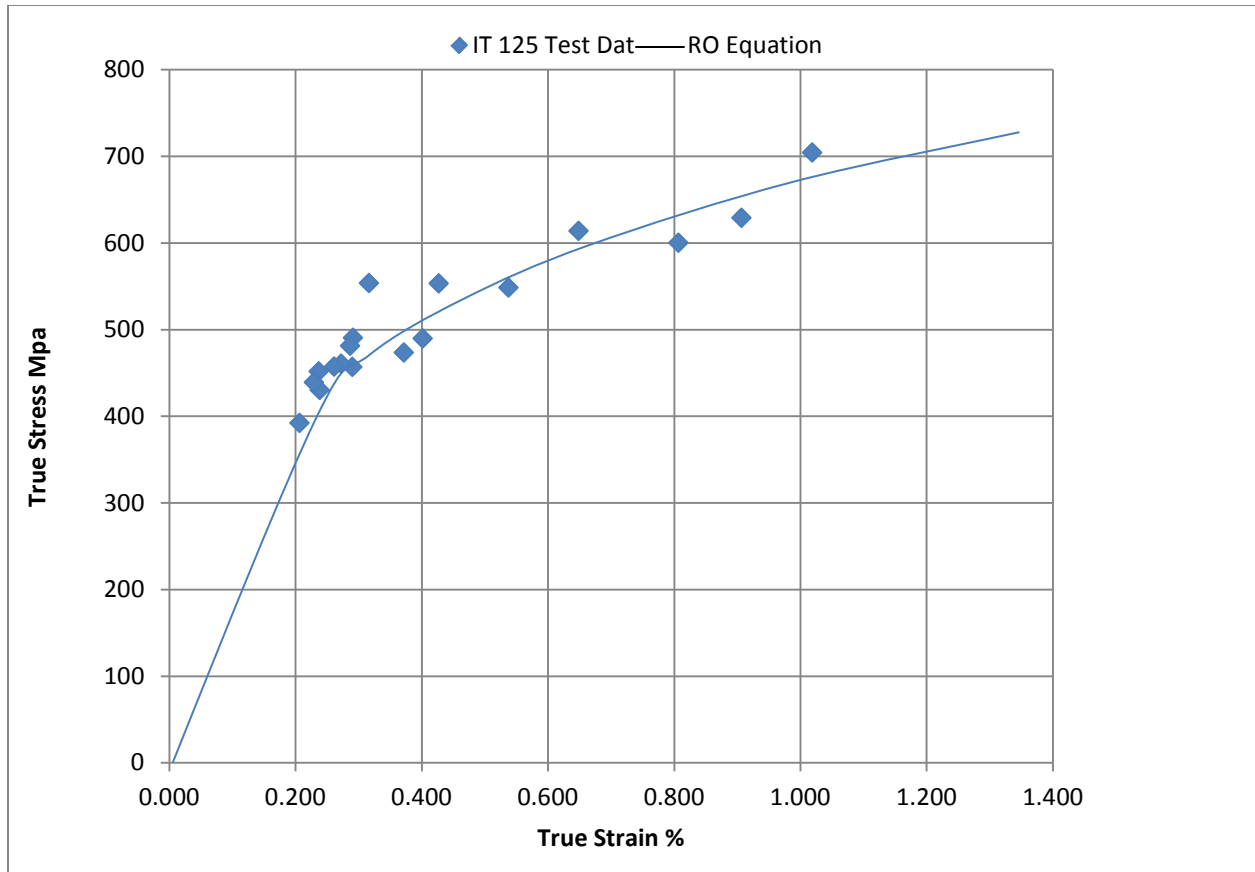


Figure 3: Cyclic true stress-strain curve for AISI 9310 (IT 125)

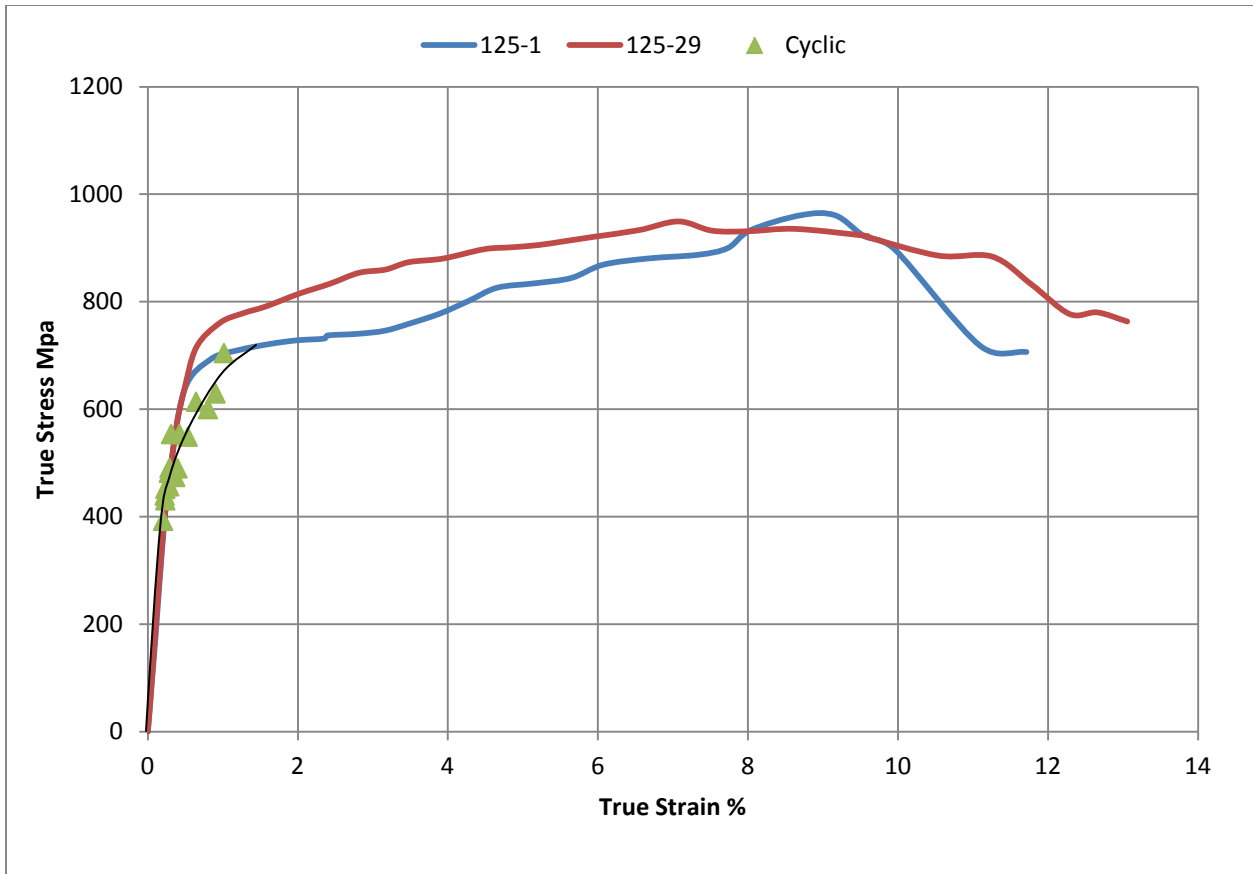


Figure 4: Monotonic & cyclic true stress-strain curves for AISI 9310 Steel (IT 125)

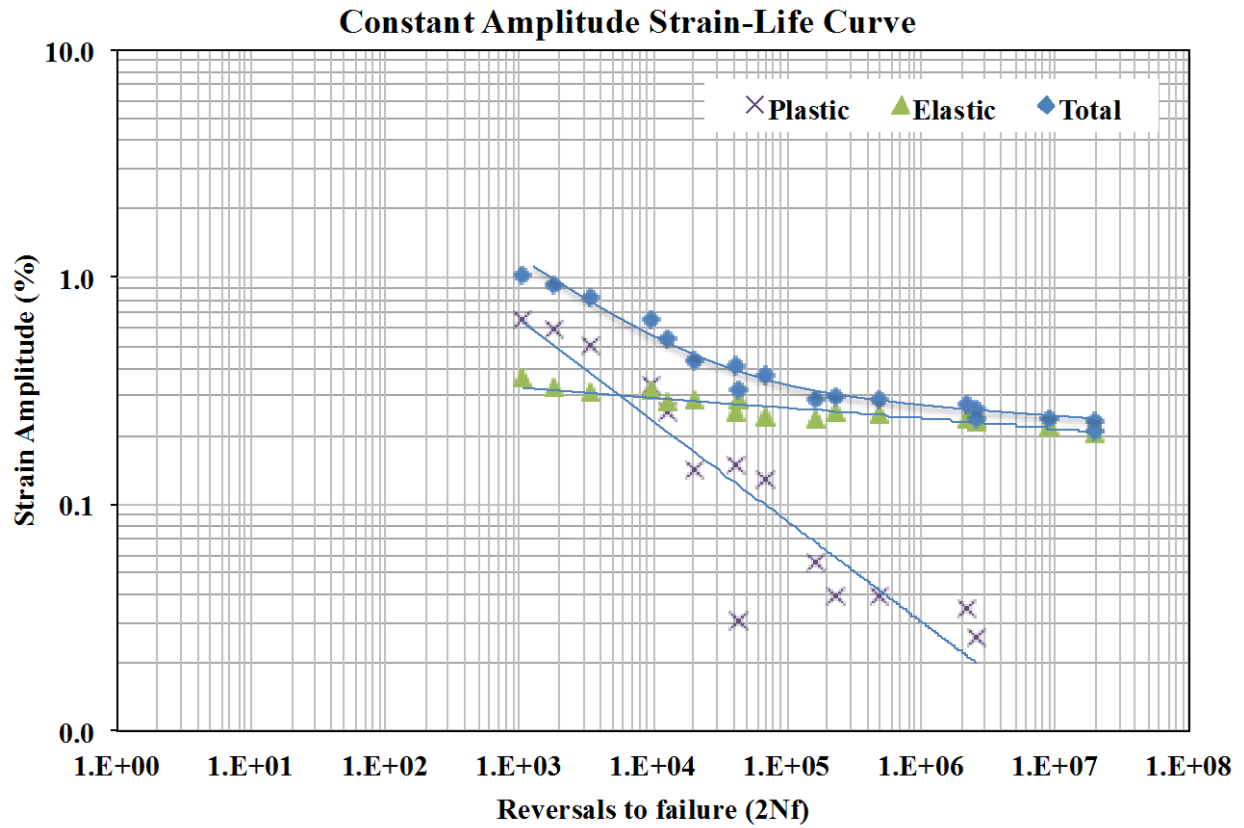


Figure 5: Strain-life fatigue curves for AISI 9310 (IT 125)

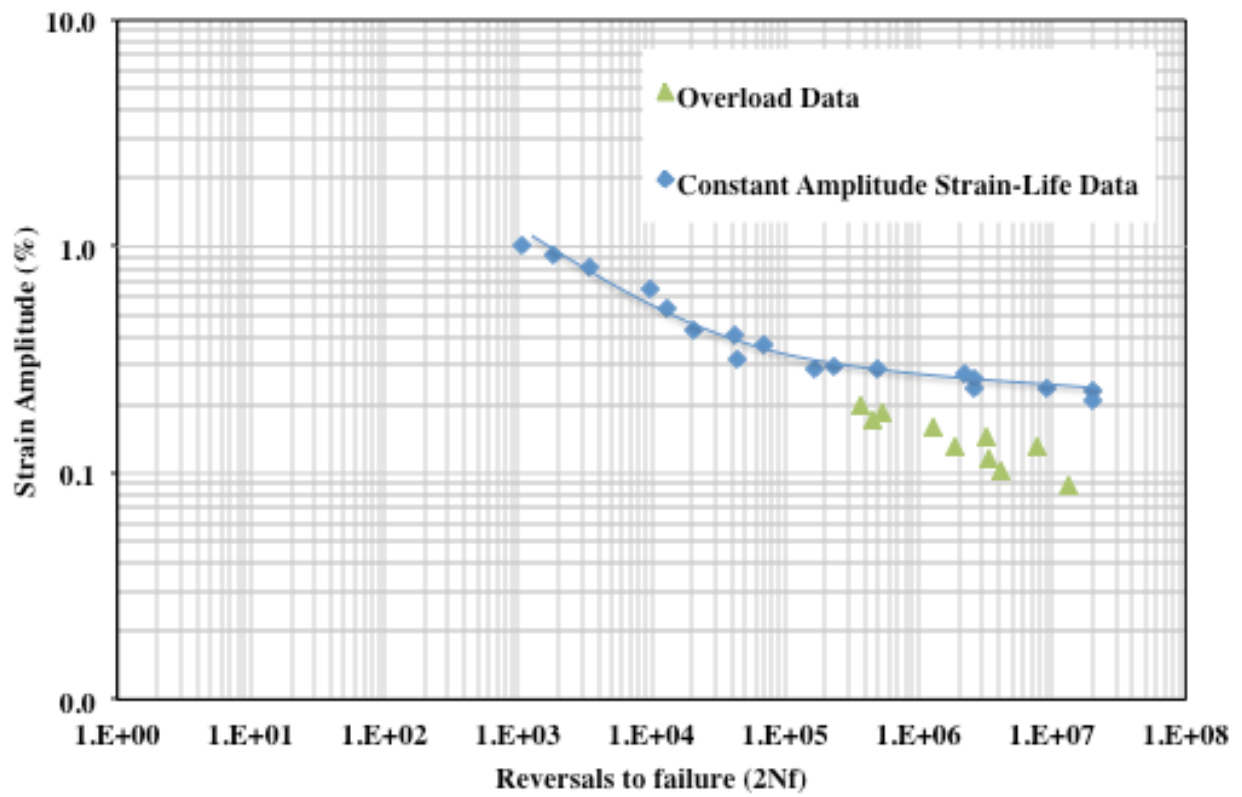


Figure 6: Overload and constant fatigue curves for AISI 9310 (IT 125)



Figure 7: Microstructure of Iteration 125/149, low magnification



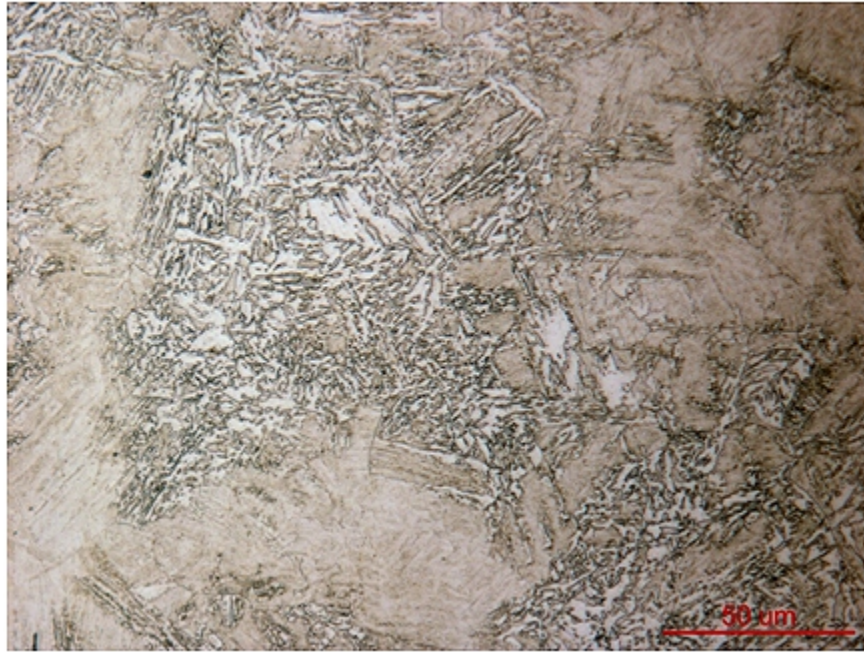


Figure 8: Microstructure of Iteration 125/149, high magnification

**Table 1: Chemical Analysis (Bar Average) for AISI 9310 Steel  
(Iterations 125 and 149)**

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

**Table 2: Monotonic and Cyclic Properties for AISI 9310 Steel  
(IT 125 and 149)**

<u>Monotonic Properties</u>	
Average elastic modulus, E (GPa)	196.4
Yield strength (MPa)	666
Ultimate tensile strength (MPa)	883
% Elongation (%)	13.2%
% Reduction of area (%)	61.4%
True fracture strain, $Ln (A_i / A_f)$ (%)	89.9%
True fracture stress, $\sigma_f = \frac{P_f}{A_f}$ (MPa)	1596
Monotonic tensile strength coefficient, K (MPa)	1235
Monotonic tensile strain hardening exponent, n	0.113
Hardness, Rockwell C (HRC)	28.6
<u>Cyclic Properties</u>	
Cyclic Yield Strength, (0.2% offset) = $K'(0.002)^{n'}$ (MPa)	536
Cyclic strength coefficient, K' (MPa)	1018
Cyclic strain hardening exponent, n'	0.097
Cyclic elastic modulus, $E_c$ (GPa)	196.4
Fatigue strength coefficient, $\sigma_f'$ (MPa)	1014
Fatigue strength exponent, b	-0.056
Fatigue ductility coefficient, $\epsilon_f'$	0.451
Fatigue ductility exponent, c	-0.56

**Table 3: Constant Strain Amplitude Data for AISI 9310 Steel (IT 125)**

Sp. #	Total Strain % Amplitude	Stress (Mpa) Amplitude	Plastic Strain % Amplitude	Elastic Strain % Amplitude	Reversals to Failure (2Nf)	Hardness HRC
10	1.024	697	0.656	0.363	1,068	Average of nine Readings HRC 28.6
13B	0.911	623	0.583	0.324	1,824	
12B	0.810	595	0.498	0.309	3,488	
15	0.651	610	0.332	0.316	9,634	
20	0.540	546	0.255	0.283	12,848	
11	0.428	551	0.142	0.285	20,756	
27	0.403	488	0.149	0.252	42,826	
26	0.373	472	0.128	0.244	69,274	
6	0.317	552	0.031	0.285	43,962	
14	0.292	489	0.039	0.253	235,036	
24	0.291	455	0.055	0.235	169,794	
19	0.287	480	0.039	0.248	486,142	
16	0.273	459	0.035	0.237	2,243,232	
7	0.262	456	0.026	0.236	2,591,194	
23	0.239	429	0.017	0.222	8,945,428	
9	0.238	450	0.005	0.233	2,562,944	
13	0.230	438	0.003	0.226	20,000,000	
12	0.207	391	0.005	0.202	20,000,000	

**Table 4: Overload Data for AISI 9310 Steel (IT 149)**

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	392	0.199	100	155,641	182,499	364998
22	365	0.186	100	214,293	270,047	540094
5	338	0.172	200	207,231	230,050	460100
25	311	0.158	200	485,817	638,556	1277112
17	284	0.144	350	1,095,822	1,590,987	3181974
2	257	0.131	500	798,303	948,233	1896466
3	257	0.131	100	793,456	3,805,814	7611628
4	230	0.117	600	1,306,822	1,668,128	3336256
21	203	0.103	1,000	1,738,737	2,102,902	4205804
18	176	0.089	2,000	4,966,482	6,604,574	13209148