PERIODIC OVERLOAD TESTS OF QUENCHED AND TEMPERED STEEL 4140

Iteration #116, 117 & 118

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TABLE OF CONTENTS

NOMENCLATURE

A_o, A_f	initial, final area	S	engineering stress
HB, HRB, HRC	Brinell, Rockwell B-Scale, Rockwell C-Scale Hardness number	YS, UYS, LYS, YS'	Monotonic yield, upper yield, lower yield, cyclic yield strength
b, c, n	fatigue strength, fatigue ductility, strain hardening exponent	YPE	yield point elongation
D_o, D_f	initial, final diameter	S_u	ultimate tensile strength
e	engineering strain	%EL	percent elongation
E, E'	monotonic, midlife cycle modulus of elasticity	%RA	percent reduction in area
K, K'	monotonic, cyclic strength coefficient	σ, σ_f, σ_f'	true stress, true fracture strength, fatigue strength coefficient
L_o, L_f	initial, final gage length	σ_a, σ_m, $\Delta\sigma$	stress amplitude, mean stress, stress range
$N_{50\%}$, $(N_f)_{10\%}$, $(N_f)_{50\%}$,	number of cycles to midlife, 10% load drop, 50% load drop,	ε_e, ε_p, ε	true elastic, plastic, total strain
$2N_f$	reversals to failure	ε_f, ε_f'	true fracture ductility, fatigue ductility coefficient
P_f, P_u	fracture, ultimate load	ε_a, ε_m, $\Delta\varepsilon$	strain amplitude, mean strain, strain range
R	strain ratio, neck radius	$\Delta\varepsilon_e$, $\Delta\varepsilon_p$	elastic, plastic strain range

NOMENCLATURE

$\sigma_{m, SC}$	small cycle mean stress	$\sigma_{a, SC}$	small cycle stress amplitude
$\sigma_{m, OL}$	overload cycle mean stress	$\sigma_{a, OL}$	overload cycle stress amplitude
$\varepsilon_{a, SC}$	small cycle strain amplitude	$(\Delta\varepsilon_p/2)_{SC}$	small cycle plastic strain amplitude,
$\varepsilon_{a, OL}$	overload cycle strain amplitude	$(\Delta\varepsilon_p/2)_{OL}$	overload plastic strain amplitude
$\varepsilon_{m, SC}$	small cycle mean strain	B, B_f	number of blocks in a periodic overload test, number of blocks to failure in a periodic overload test
N_{SC}, $N_{f, SC(eq)}$	number of small cycles in an overload block, calculated equivalent life of the small cycles in an overload test	$N_{f, OL}$	Constant amplitude life to failure at the strain amplitude used for the periodic overload cycle amplitude

UNIT CONVERSION TABLE

Measure	SI Unit	US Unit	from SI to US	from US to SI
Length	mm	in	1 mm = 0.03937 in	1 in = 25.4 mm
Area	mm^2	in^2	1 mm^2 = 0.00155 in^2	1 in^2 = 645.16 mm^2
Load	kN	klb	1kN = 0.2248 klb	1 klb = 4.448 kN
Stress	MPa	ksi	1 MPa = 0.14503 ksi	1 ksi = 6.895 MPa
Temperature	^oC	^oF	$^oC = (^oF - 32)/1.8$	$^oF = (^oC * 1.8) + 32$

In SI Unit:	1 kN = 10^3 N	1 Pa = 1 N/m^2	1 MPa = 10^6 Pa = 1 N/mm^2	1 Gpa = 10^9 Pa
In US Unit:	1 klb = 10^3 lb	1 psi = 1 lb/in^2	1 ksi = 10^3 psi	

SUMMARY

Periodic overload fatigue data were obtained for the steel material of iterations 116, 117, and 118. The material was provided by AISI. Two constant amplitude fully reversed tests were performed for each iteration to verify that fatigue behaviors were the same as those obtained in previous constant amplitude testing performed in iterations 99, 80, and 81. Periodic overload and fatigue behaviors were obtained from eleven, eleven, and thirteen specimens for iterations 116, 117, and 118, respectively. The experimental procedure followed and results obtained are presented and discussed in this report.

I. EXPERIMENTAL PROGRAM

1.1 Material and Specimen Fabrication

1.1.1 Material

The steel material was provided by AISI. The test specimens were prepared from a 4140 steel grade. Six inch square continuous cast billets were forged into 2.5" square from which 0.625" wide slabs were cut lengthwise. Then coupons of 0.625" wide slices in the transverse direction were cut from them. The rough specimens were then machined from 0.625"x0.625"x2.5" square cross-section coupons at the University of Toledo. The machined rough specimens were heat treated to a desired hardness of 40 HRC at Chrysler and then sent to be ground to the final dimensions. The chemical compositions of iterations 116, 117, and 118 are shown in Tables 1, 2, and 3, respectively. The chemistry for these iterations, which were originally provided by Macsteel Company, was taken from the final reports of iterations 99, 80, and 81.

1.1.2 Specimen

In this study, identical round specimens were used for monotonic and fatigue tests. The specimen configuration and dimensions are shown in Figure 1. This configuration deviates slightly from the specimen geometry recommended by ASTM Standard E606 [1]. The recommended specimens have uniform gage sections. The specimen geometry shown in Figure 1 differs by using a large secondary radius in the gage section to compensate for the slight stress concentration at the gage to grip section transition.

Before heat treatment and grinding, rough machining of the specimen was performed in the Mechanical, Industrial, and Manufacturing Engineering Machine Shop at the University of Toledo. The specimens were initially turned on a lathe to an appropriate diameter for insertion into a CNC/milling machine. Using the CNC machine, final turning was performed to achieve slightly oversized dimensions then those specified on the specimen drawings.

After heat treatment and grinding, the specimens were then polished prior to testing at the University of Toledo. A commercial round-specimen polishing machine was used to polish the specimen gage section. Three different grits of aluminum oxide lapping film 30 μm, 12 μm, and 3 μm were used. Polishing marks coincided with the longitudinal direction of the specimen. The polished surfaces were carefully examined under magnification to ensure complete removal of machine marks within the test section.

1.2 Testing Equipment

1.2.1 Apparatus

An MTS closed-loop servo-controlled hydraulic axial load frame in conjunction with a Fast-Track digital servo-controller was used to conduct the tests. The load cell used had a capacity of 100 kN. Hydraulically operated grips using universal tapered collets were employed to secure the specimens' ends in series with the load cell.

Total strain was controlled using an extensometer rated as ASTM class B1 [2]. The calibration of the extensometer was verified using displacement apparatus containing a micrometer barrel in divisions of 0.0001 in. The extensometer had a gage length of 0.236 in. and was capable of measuring strains from -5% to 10 %.

In order to protect the specimens' surface from the knife-edges of the extensometer, ASTM Standard E606 recommends the use of transparent tape or epoxy to 'cushion' the attachment. For this study, it was found that application of transparent tape allowed for more consistency of the material thickness between the knife edge and the specimen. Therefore, transparent tape was considered to be the best protection. The tests were performed using three layers of transparent tape.

1.2.2 Alignment

Significant effort was put forth to align the load train (load cell, grips, specimen, and actuator). Misalignment can result from both tilt and offset between the central lines of the load train components. In order to align the machine, a round strain-gage bar was used. The Strain-gage bar has two arrays of four strain gages per array with one array arranged at the upper and lower ends of the uniform gage section. This was done in accordance with ASTM Standard E1012 [3].

1.3 Test Methods and Procedures

The overload tests were conducted to investigate the effects of periodic overloads on the fatigue life of smaller subsequent cycles. For this study, 11 specimens were tested at 5 different strain amplitudes for iteration 116, 11 specimens were tested at 4 different strain amplitudes for iteration 117, and 13 specimens were tested at 5 different strain amplitudes for iteration 118.

For iteration 116, all but two of the tests were performed in load-control after an initial 1,000 pre-cycles at the overload level in strain-control. For iteration 117, all of the tests were performed in load-control after an initial 1,000 pre-cycles at the overload level in strain-control. For iteration 118, all but one of the tests were performed in load-control without the initial pre-cycles. One test for iteration 118 was performed in load-control after an initial 1,000 pre-cycles at the overload level in strain-control. The periodic overload tests were performed with INSTRON WAVERUNNER software. During each test, the total strain was recorded using the extensometer output. Test data were automatically recorded throughout each test.

The input signal consisted of a periodic fully reversed overload of the type shown in Figure 2. The load history in these tests consisted of repeated blocks made up of one fully-reversed overload cycle followed by a group of smaller constant amplitude cycles having the same maximum stress as the overload cycle. The overload cycles were applied at frequent intervals to maintain a larger effective strain range resulting in the subsequent cycles being fully effective.

With this overload history, as the large cycles become more frequent, the fraction of the total damage done by them increases and that done by the small cycles decreases. The fully reversed strain amplitude for the overload cycle corresponded to about 10^4 cycles to failure. The number of small cycles per block, N_{sc}, were adjusted so that they cause 80% to 90% of the damage per block. Small cycle strain levels were selected at or below the run out level of the constant amplitude tests. Small cycle strain amplitudes were used from 0.062% to 0.324% for iteration 116, 0.062% to 0.332% for iteration 117, and 0.060% to 0.240% for iteration 118. The number of small cycles per overload cycle ranged between 16 and 900 for iteration 116, 30 and 3076 for iteration 117, and 32 and 2400 for iteration 118.

For the load-controlled tests, calculations were performed based on the true stress-strain behavior characterized by the Ramberg-Osgood type equation:

$$\frac{\Delta \varepsilon}{2} = \frac{\Delta \varepsilon_e}{2} + \frac{\Delta \varepsilon_p}{2} = \frac{\Delta \sigma}{2E} + \left(\frac{\Delta \sigma}{2K'}\right)^{\frac{1}{n'}} \quad (1)$$

The constants for this equation were obtained from the previously performed constant amplitude testing of iterations 80, 81, and 99. This calculation was performed in order to arrive at the steady state stress amplitudes for the desired strain amplitudes. Due to the transient response of the material, the calculated loads would result in a lower than expected strain amplitude throughout the test. In order to reduce cyclic transient behavior, 1000 strain-controlled pre-cycles were applied at the periodic overload strain level. After completion of these initial cycles the second portion of the test was started using the previously mentioned periodic overload history.

II. EXPERIMENTAL RESULTS AND ANALYSIS

Periodic Overload fatigue tests were performed to determine the effective strain-life curve. The effective strain-life curve is plotted using the strain amplitude of the small cycles in the overload block and the calculated equivalent life. The equivalent fatigue life for the smaller cycles was obtained using the linear damage rule:

$$\frac{N_{OL}}{N_{f,OL}} + \frac{N_{SC}}{N_{f,SC(eq)}} = 1 \tag{13}$$

where N_{OL} is the number of overload cycles in a periodic overload test, $N_{f,OL}$ is the number of cycles to failure if only overloads were applied in a test, N_{SC} is the number of smaller cycles in a periodic overload test, and $N_{f,SC(eq)}$ is the computed equivalent fatigue life for the smaller cycles.

The linear damage rule was also used to calculate the cumulative damage of the overload cycles, D_{OL}, as

$$\frac{N_{OL}}{N_{f,OL}} = D_{OL} \tag{14}$$

Figures 3, 5, and 7 shows the effective strain-life data superimposed on the constant amplitude strain life plot for iterations 116, 117, and 118 respectively. Tables A-1, A-2, and A-3 present a summary of the periodic overload test results for iteration 116, 117 and 118 respectively. Figure 9 shows a comparison of the effective and constant amplitude strain-life data for each of the three iterations superimposed on a strain-life plot.

A plot of the SWT parameter for both the constant amplitude and overload data provides another method of comparison between the constant amplitude and periodic overload data, where the mean stress present in the small cycles is taken into account. The SWT parameter is given by

$$\sigma_{max}\varepsilon_a = \frac{1}{E}[(\sigma_f')^2(2N_f)^{2b} + \sigma_f'\varepsilon_f' E(2N_f)^{b+c}] \tag{15}$$

where $\sigma_{max} = \sigma_m + \sigma_a$. The SWT plot for iterations 116, 117, and 118 is shown in Figures 4, 6, and 8 respectively. As in the constant amplitude strain-life curve, the overload data and effective strain-life curve diverged from the constant amplitude curve.

Table 1: Chemical Composition of SAE 4140 (0.004 max S) Steel

Element	**Wt. %**
Carbon, C	0.410%
Manganese, Mn	0.870%
Silicon, Si	0.240%
Chromium, Cr	0.900%
Nickel, Ni	0.050%
Molybdenum, Mo	0.180%
Copper, Cu	0.100%
Phosphorus, P	0.010%
Sulfur, S	0.004%
Aluminum, Al	0.020%
Tin, Sn	0.005%
Nitrogen, N	0.0058%
DI	4.800%

Table 2: Chemical Composition of SAE 4140 (0.012 max S) Steel

Element	**Wt. %**
Carbon, C	0.412%
Manganese, Mn	0.940%
Silicon, Si	0.280%
Chromium, Cr	1.010%
Nickel, Ni	0.150%
Molybdenum, Mo	0.220%
Copper, Cu	0.170%
Phosphorus, P	0.010%
Sulfur, S	0.012%
Aluminum, Al	0.028%
Tin, Sn	0.007%
Nitrogen, N	0.0094%
DI	6.400%

Table 3: Chemical Composition of SAE 4140 (0.077 max S) Steel

Element	Wt. %
Carbon, C	0.404%
Manganese, Mn	0.850%
Silicon, Si	0.280%
Chromium, Cr	0.990%
Nickel, Ni	0.150%
Molybdenum, Mo	0.220%
Copper, Cu	0.170%
Phosphorus, P	0.010%
Sulfur, S	0.012%
Aluminum, Al	0.010%
Tin, Sn	0.009%
Nitrogen, N	N/A
DI	5.840%

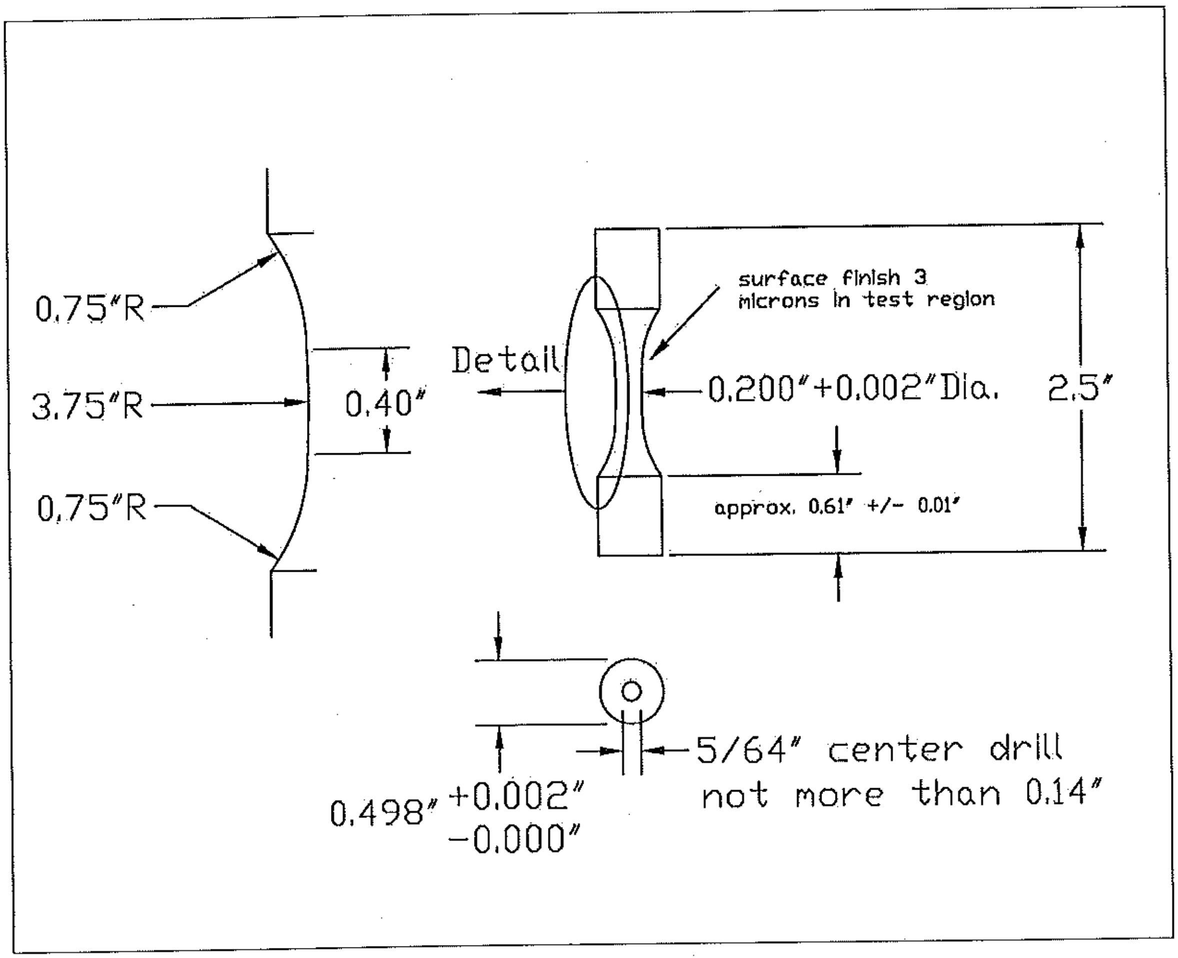

Figure 1: Specimen configuration and dimensions (in.)

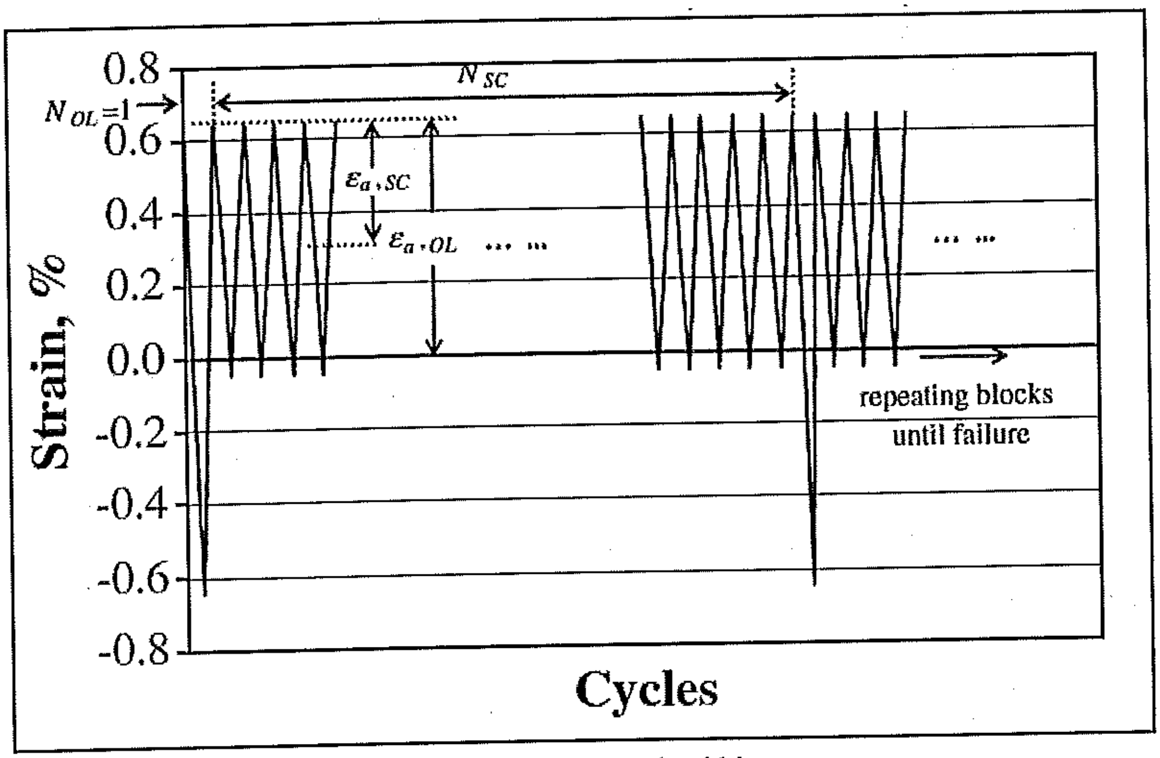

Figure 2: Periodic overload history

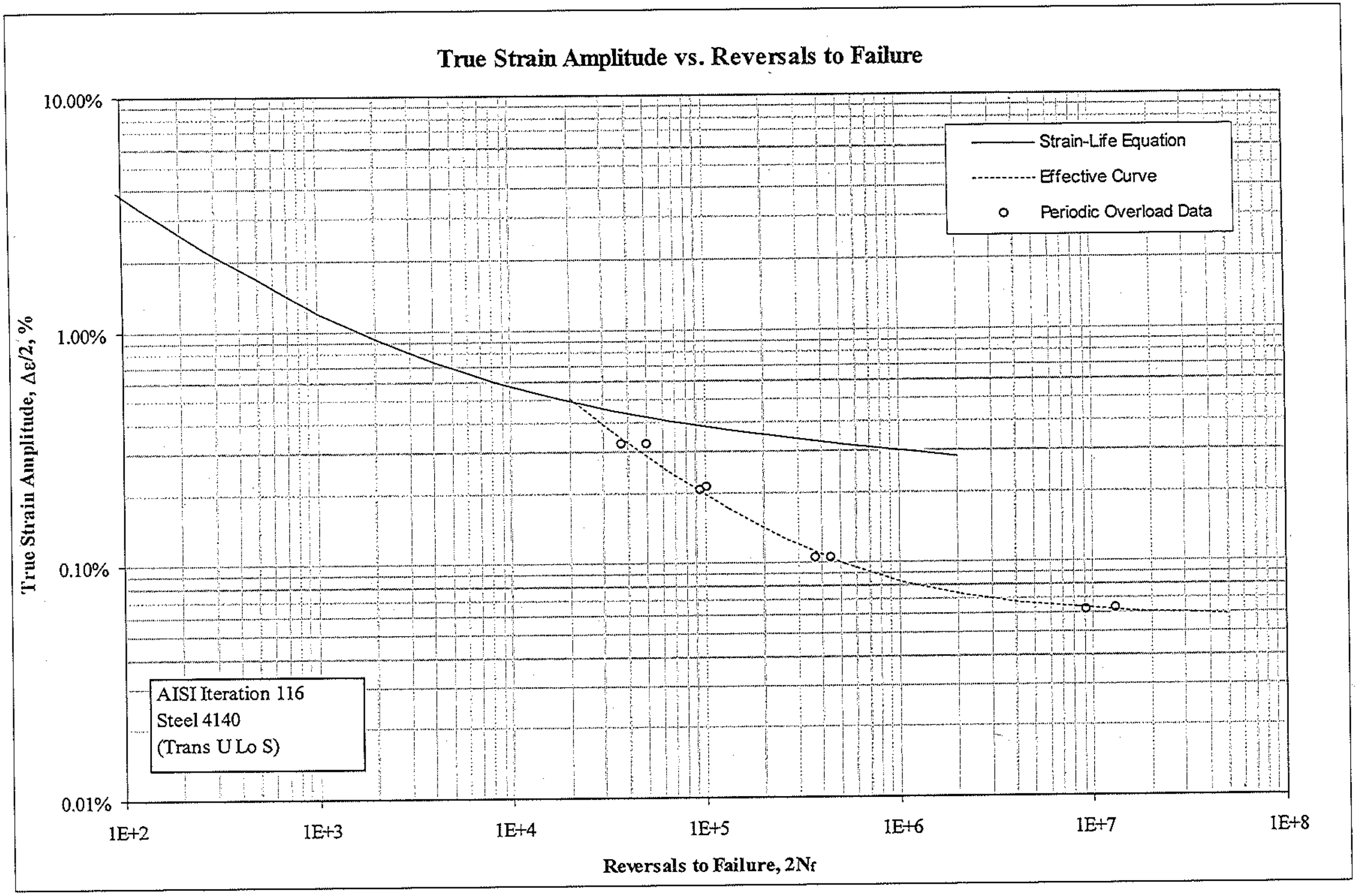

Figure 3: Periodic overload data for iteration 116 superimposed with the constant amplitude fatigue equation.

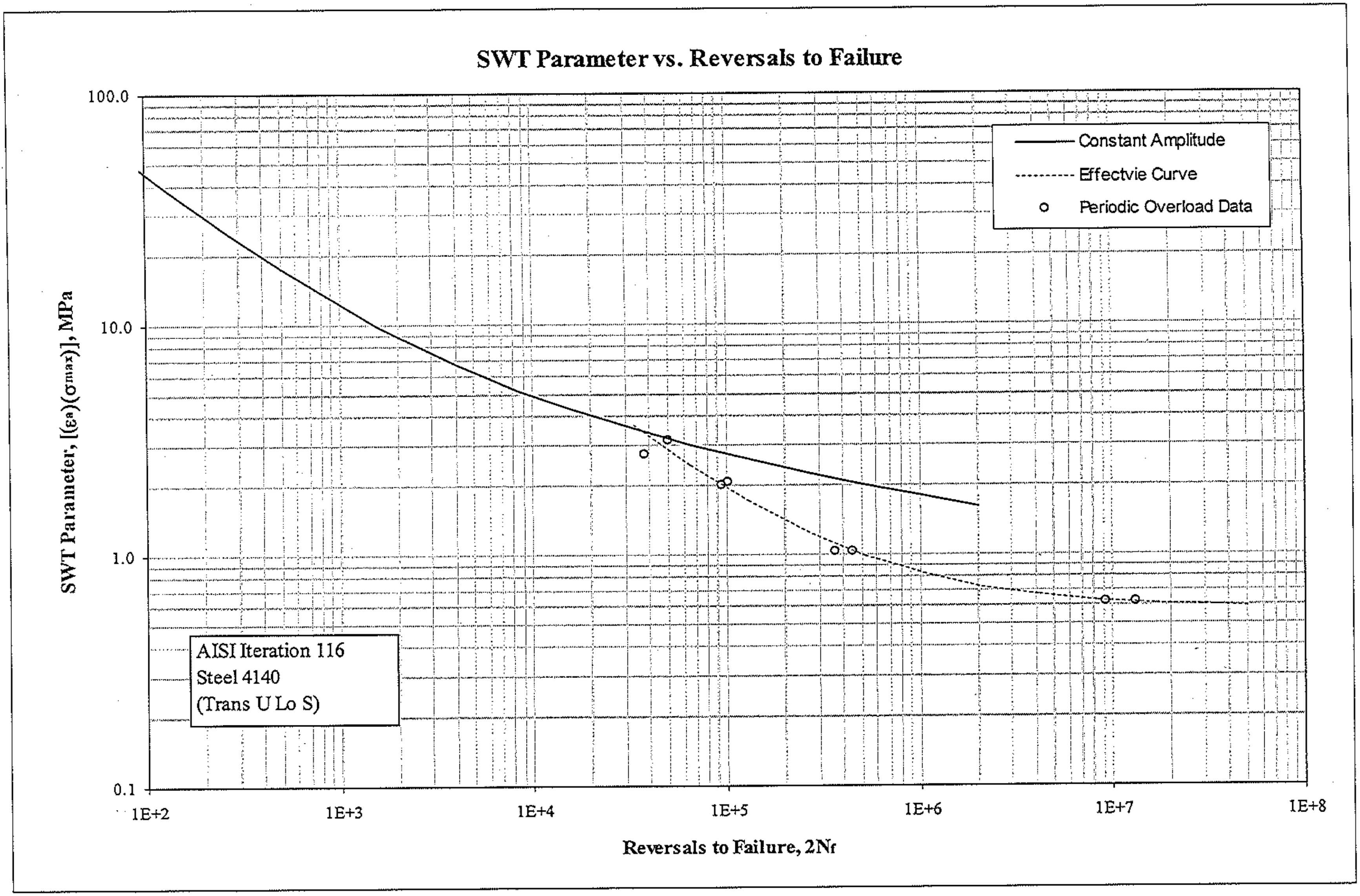

Figure 4: SWT parameter versus reversals to failure. Periodic overload data superimposed on the constant amplitude equation

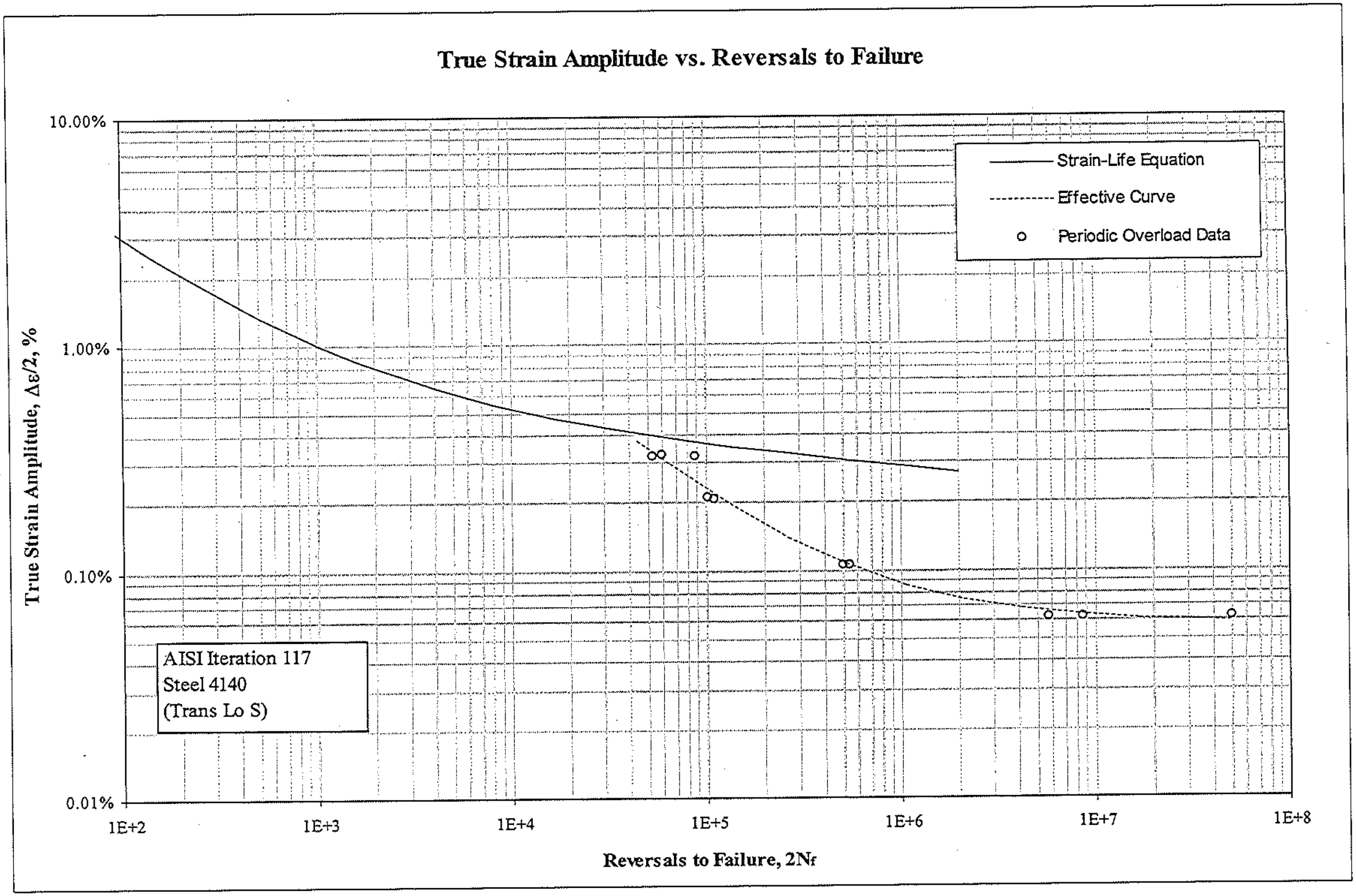

Figure 5: Periodic overload data for iteration 117 superimposed with the constant amplitude fatigue equation

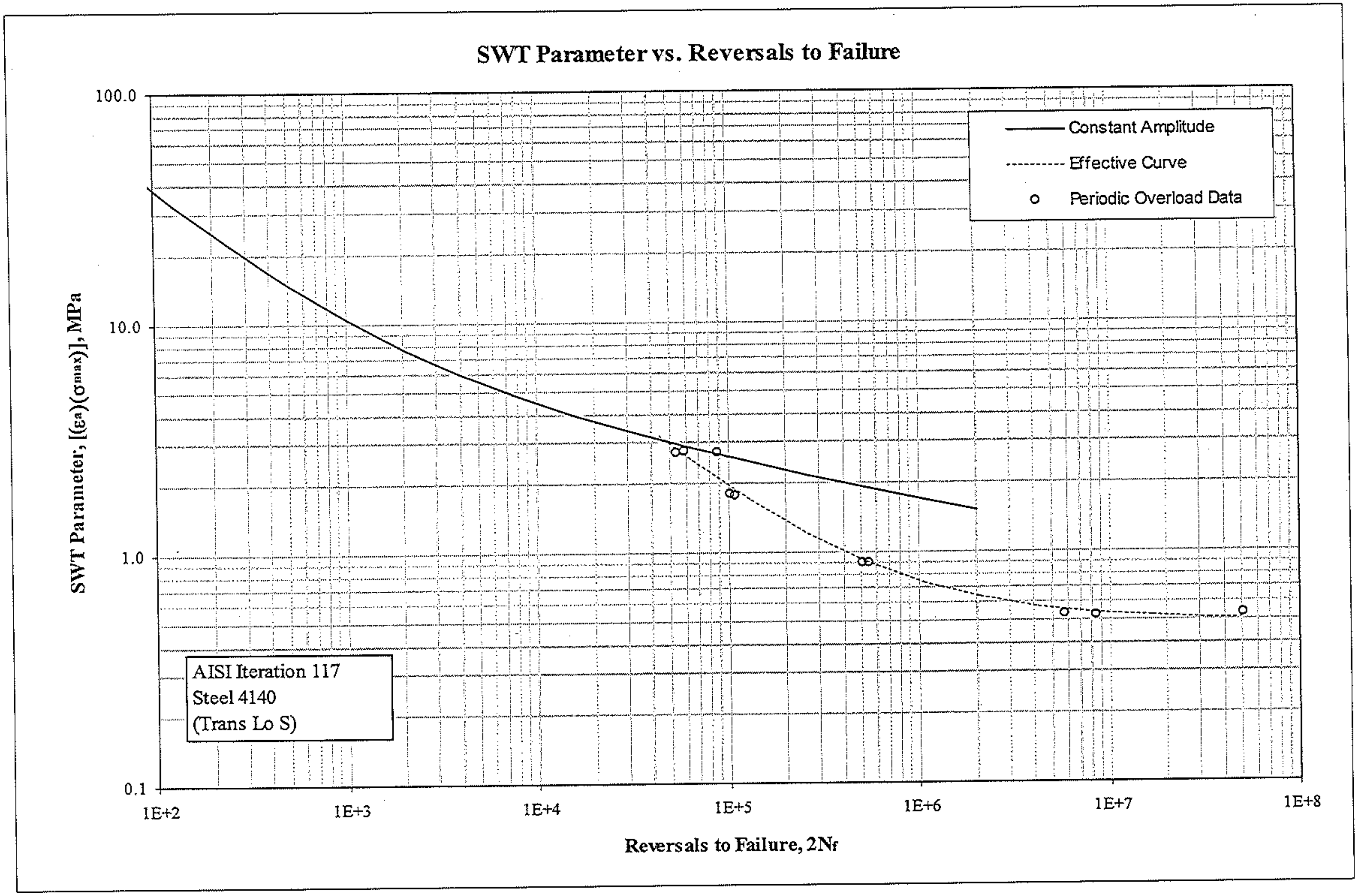

Figure 6: SWT parameter versus reversals to failure. Periodic overload data superimposed on the constant amplitude equation

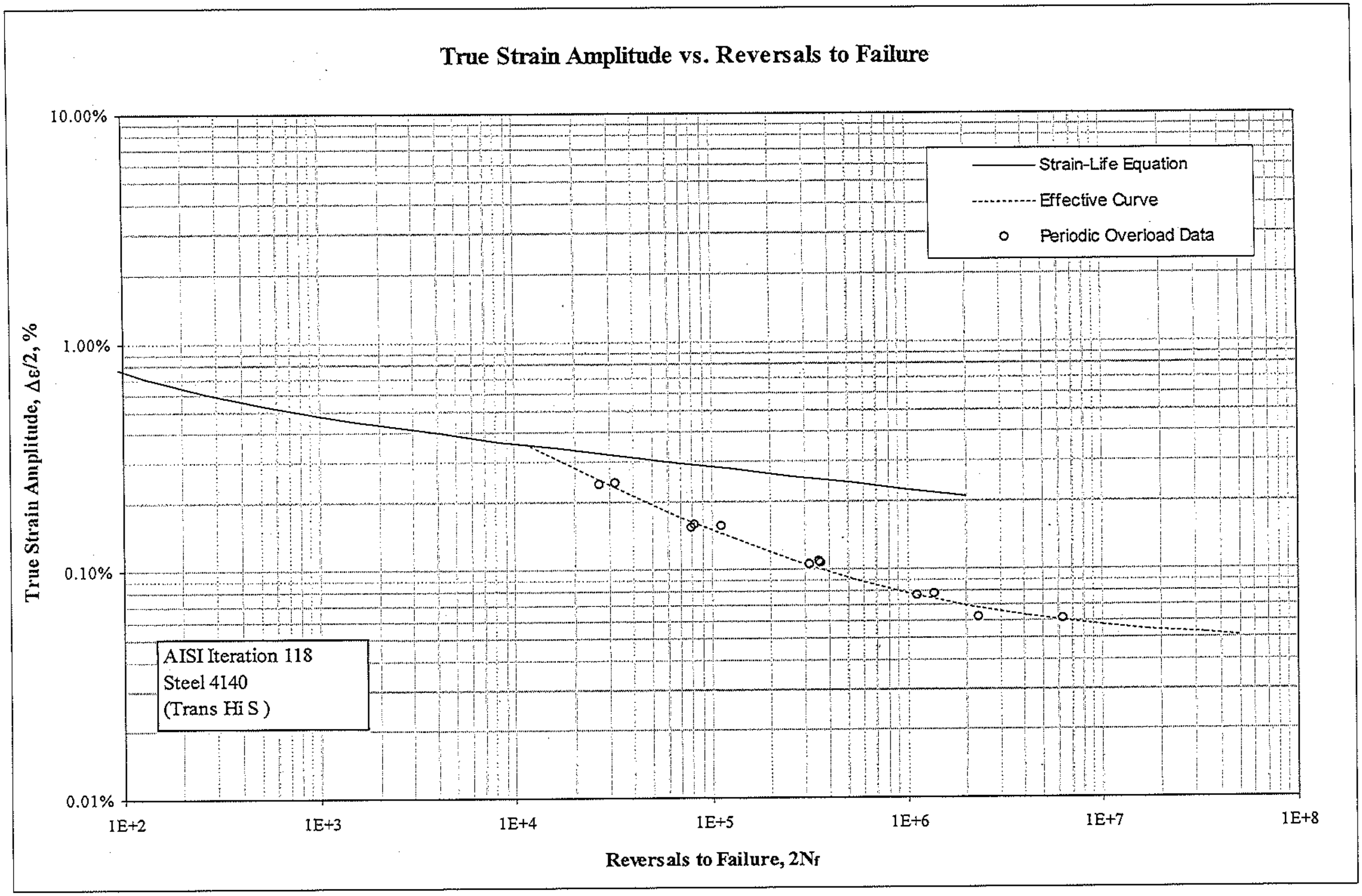

Figure 7: Periodic overload data for iteration 118 superimposed with the constant amplitude fatigue equation

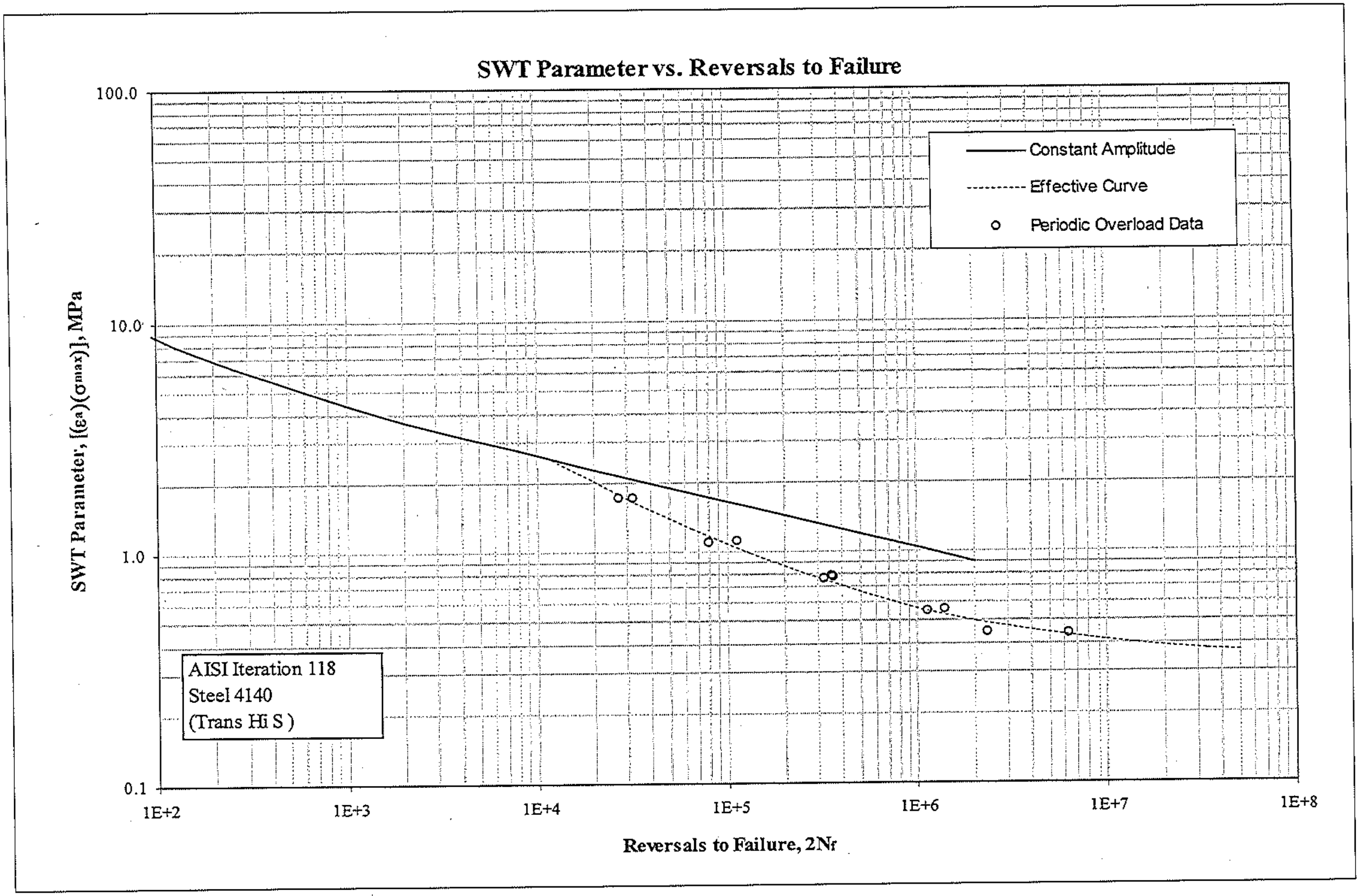

Figure 8: SWT parameter versus reversals to failure. Periodic overload data superimposed on the constant amplitude equation

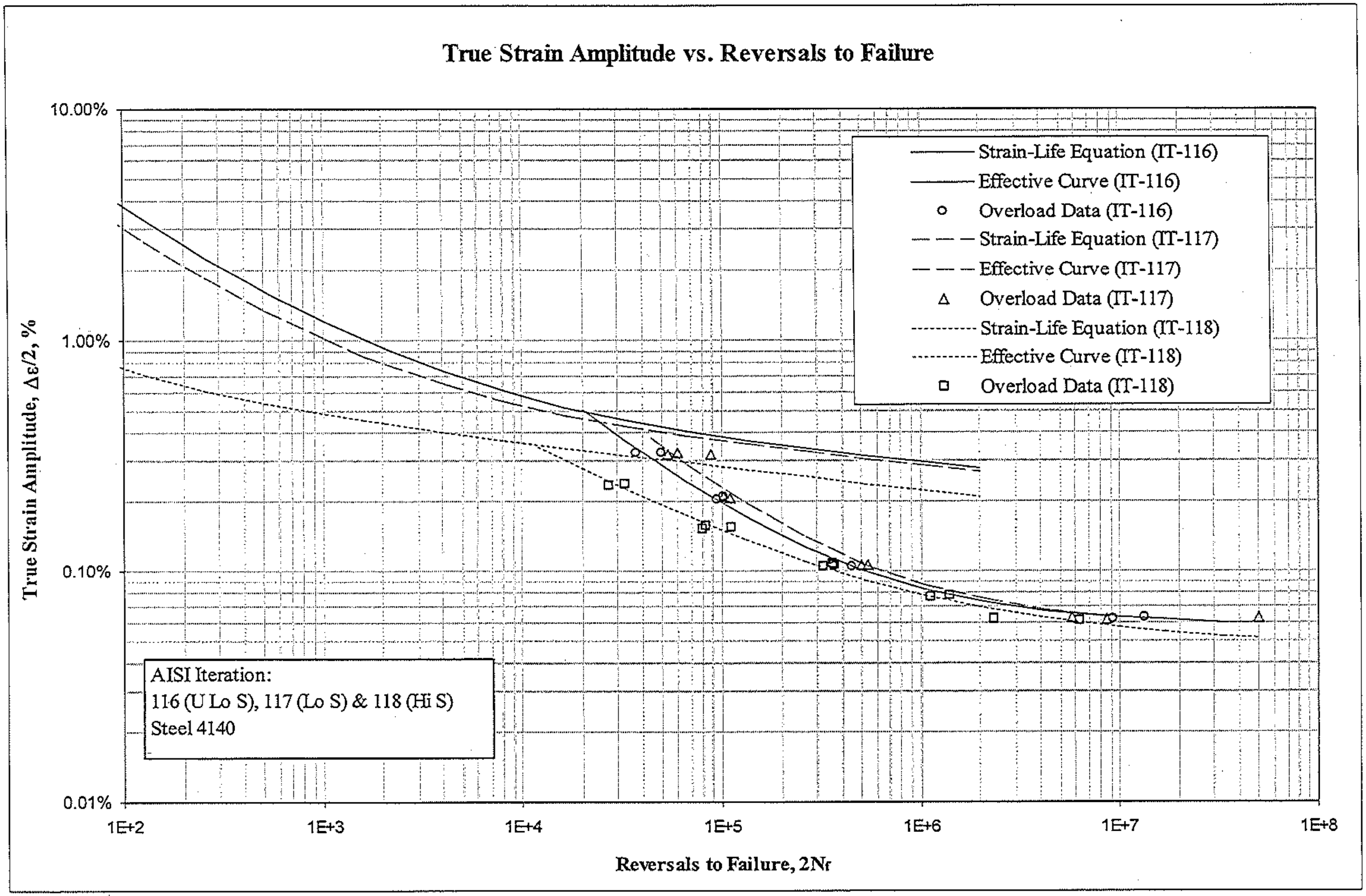

Figure 9: Periodic overload data for iteration 116, 117, and 118 superimposed with their respective constant amplitude fatigue equation

REFERENCES

[1] ASTM Standard E606-92, "Standard Practice for Strain-Controlled Fatigue Testing," Annual Book of ASTM Standards, Vol. 03.01, 2004, pp. 593-606.

[2] ASTM Standard E83-02, "Standard Practice for Verification and Classification of Extensometers," Annual Book of ASTM Standards, Vol. 03.01, 2004, pp. 232-244.

[3] ASTM Standard E1012-99, "Standard Practice for Verification of Specimen Alignment Under Tensile Loading," Annual Book of ASTM Standards, Vol. 03.01, 2004, pp. 763-770.

APPENDIX A

Table A-1 : Summary of the periodic overload fatigue test results

Spec. ID	Test Control Mode [c]	Test Freq. OL/SC (Hz)	Load history Description: $\varepsilon_{a,SC}$ (%)	$\varepsilon_{m,SC}$ (%)	$\Delta\varepsilon_p/2_{,SC}$ (calculated) (%)	$\sigma_{a,SC}$ (MPa) [b]	$\sigma_{m,SC}$ (MPa) [b]	N_{SC} (Cycles)	$\varepsilon_{a,OL}$ (%)	$\Delta\varepsilon_p/2_{,OL}$ (calculated) (%)	$\sigma_{a,OL}$ (MPa) [b]	$\sigma_{m,OL}$ (MPa) [b]	$N_{f,OL}$ (Cycles)	Exp. Life (Blks)	$N_{f,sc(eq)}$ (Cycles)	OL Damage Ratio	Failure Location [a]
116_03	strain	2	0.324%	0.176%	0.011%	651.6	311.9	16	0.501%	0.017%	1006.1	-39.1	9,415	1,345	25,107	0.143	IGL
116_04	strain	2	0.324%	0.175%	0.011%	653.0	184.1	16	0.501%	0.012%	1017.7	-176.0	9,415	1,042	18,747	0.111	IGL
116_05	load	2.4	0.211%	0.276%	0.010%	417.6	569.3	64	0.505%	0.029%	991.0	-0.2	9,048	655	50,969	0.178	IGL
116_06*	load	2.4	0.210%	0.199%	0.010%	417.2	569.8	64	0.500%	0.024%	990.8	-0.5	9,510	297	22,010	0.136	IGL
116_11*	load	2.4	0.205%	0.315%	0.005%	416.5	569.7	64	0.486%	0.012%	987.8	1.5	11,000	233	17,068	0.126	IGL
116_13	load	2.4	0.204%	0.259%	0.004%	416.3	570.0	64	0.501%	0.026%	989.5	1.0	9,415	609	46,950	0.170	IGL
116_09	load	4	0.105%	0.425%	0.007%	204.3	783.0	166	0.522%	0.046%	990.9	-0.8	7,706	862	182,752	0.217	IGL
116_07	load	4	0.105%	0.371%	0.007%	204.5	782.7	166	0.567%	0.091%	990.4	-1.3	5,311	960	223,165	0.286	IGL
116_10	load	15	0.063%	0.678%	0.004%	123.0	866.1	828	0.605%	0.129%	990.9	-0.6	4,066	2,410	6,604,763	0.698	IGL
116_12	load	15	0.062%	0.592%	0.003%	122.7	873.9	828	0.599%	0.120%	996.4	1.9	4,231	2,158	4,643,482	0.615	IGL
116_08*	load	7	0.042%	0.610%	0.003%	82.7	907.3	900	0.671%	0.194%	991.2	-0.3	2,754	3,041	-13,072,415	1.209	IGL

*Data from this test was not used in fits due to failure occuring at a surface defect.

[a] IGL = Inside gage length
[b] All stress values reported are from mid-life
[c] Load-controlled tests were pre-cycled at the OL strain amplitude of 0.50% for 1000 cycles. Damage from the pre-strained cycles is included in the OL damage ratio

Table A-2: Summary of the periodic overload fatigue test results

Spec. ID	Test Control Mode [c]	Test Freq. OL/SC (Hz)	Load history Description											Exp. Life (Blks)	$N_{f,\,sc(eq)}$ (Cycles)	OL Damage Ratio	Failure Location [a]
			$\varepsilon_{a,\,SC}$ (%)	$\varepsilon_{m,\,SC}$ (%)	$\Delta\varepsilon_p/2,_{SC}$ (calculated) (%)	$\sigma_{a,\,SC}$ (MPa) [b]	$\sigma_{m,\,SC}$ (MPa) [b]	N_{SC} (Cycles)	$\varepsilon_{a,\,OL}$ (%)	$\Delta\varepsilon_p/2,_{OL}$ (calculated) (%)	$\sigma_{a,\,OL}$ (MPa) [b]	$\sigma_{m,\,OL}$ (MPa) [b]	$N_{f,\,OL}$ (Cycles)				
117_02*	load	4	0.332%	0.114%	0.016%	652.7	195.1	30	0.434%	0.023%	849.5	0.4	14,440	148	5,334	0.168	IGL
117_11	load	4	0.325%	0.066%	0.009%	653.0	195.2	30	0.423%	0.012%	849.5	0.9	17,100	788	29,678	0.203	IGL
117_03	load	4	0.322%	0.039%	0.006%	653.1	195.0	30	0.419%	0.007%	849.6	0.9	18,240	718	26,816	0.197	IGL
117_09	load	4	0.322%	0.148%	0.006%	652.6	194.9	30	0.423%	0.011%	849.2	0.7	17,100	1,141	44,117	0.224	IGL
117_12	load	10	0.211%	0.201%	0.011%	412.8	435.1	72	0.437%	0.025%	850.1	0.2	13,820	570	51,212	0.199	IGL
117_05	load	10	0.207%	0.274%	0.007%	412.6	435.4	72	0.422%	0.010%	850.5	0.0	17,380	610	54,389	0.192	IGL
117_04	load	10	0.106%	0.360%	0.005%	206.9	642.0	316	0.434%	0.022%	850.2	0.3	14,440	634	250,834	0.201	IGL
117_06	load	10	0.106%	0.313%	0.006%	206.1	642.2	316	0.437%	0.025%	850.3	0.2	13,820	679	270,406	0.207	IGL
117_10	load	25	0.062%	0.603%	0.003%	123.1	727.1	3,076	0.421%	0.009%	850.7	-0.3	17,660	751	2,887,258	0.200	IGL
117_07	load	15	0.062%	0.316%	0.002%	123.3	725.2	1,538	0.426%	0.014%	850.6	0.3	16,310	2,000	4,272,254	0.280	IGL
117_08	load	25	0.062%	0.603%	0.002%	123.8	727.6	3,076	0.421%	0.009%	850.7	0.4	17,660	4,695	25,039,402	0.423	IGL

*Data from this test was not used in fits due to failure occuring at a surface defect.

[a] IGL = Inside gage length
[b] All stress values reported are from mid-life
[c] Load-controlled tests were pre-cycled at the OL strain amplitude of 0.50% for 1000 cycles. Damage from the pre-strained cycles is included in the OL damage ratio

Table A-3: Summary of the periodic overload fatigue test results

Spec. ID	Test Control Mode	Test Freq. OL/SC (Hz)	Load history Description: $\varepsilon_{a, SC}$ (%)	$\varepsilon_{m, SC}$ (%)	$\Delta\varepsilon_p/2_{, SC}$ (calculated) (%)	$\sigma_{a, SC}$ (MPa) [b]	$\sigma_{m, SC}$ (MPa) [b]	N_{SC} (Cycles)	$\varepsilon_{a, OL}$ (%)	$\Delta\varepsilon_p/2_{, OL}$ (calculated) (%)	$\sigma_{a, OL}$ (MPa) [b]	$\sigma_{m, OL}$ (MPa) [b]	$N_{f, OL}$ (Cycles)	Exp. Life (Blks)	$N_{f, sc(eq)}$ (Cycles)	OL Damage Ratio	Failure Location [a]
118_03	load	4	0.240%	0.129%	0.015%	459.8	257.6	32	0.376%	0.024%	719.7	0.1	3,526	443	16,213	0.126	IGL
118_08	load	4	0.237%	0.122%	0.013%	458.2	262.1	32	0.372%	0.019%	722.2	0.9	3,875	383	13,600	0.099	IGL
118_15	load [c]	4	0.157%	0.224%	0.007%	308.1	412.8	120	0.368%	0.014%	723.6	0.5	4,266	272	41,452	0.213	IGL
118_04	load	4	0.155%	0.221%	0.005%	308.0	410.6	120	0.357%	0.005%	719.1	1.1	5,607	433	56,308	0.077	IGL
118_11*	load	4	0.155%	0.234%	0.004%	308.4	415.6	120	0.360%	0.005%	724.7	1.8	5,197	124	15,244	0.024	IGL
118_14	load	4	0.152%	0.219%	0.001%	308.3	411.8	120	0.361%	0.009%	721.7	2.1	5,069	312	39,896	0.062	IGL
118_13	load	8	0.108%	0.287%	0.008%	204.9	515.7	254	0.387%	0.034%	721.1	2.0	2,743	560	178,729	0.204	IGL
118_05	load	8	0.107%	0.243%	0.006%	205.9	515.2	254	0.372%	0.019%	723.4	0.5	3,875	605	182,101	0.156	IGL
118_12	load	8	0.106%	0.229%	0.005%	206.7	515.4	254	0.377%	0.024%	722.5	2.9	3,444	533	160,170	0.155	IGL
118_06	load	10	0.078%	0.183%	0.003%	153.7	564.3	1,200	0.361%	0.009%	718.7	1.7	5,069	520	695,330	0.103	IGL
118_10	load	10	0.077%	0.376%	0.002%	153.7	562.6	1,200	0.368%	0.019%	714.8	3.2	4,266	423	563,472	0.099	IGL
118_09	load	15	0.061%	0.331%	0.003%	119.6	599.5	2,400	0.372%	0.020%	719.3	1.5	3,875	432	1,166,889	0.111	IGL
118_07	load	15	0.060%	0.451%	0.002%	119.2	599.6	2,400	0.383%	0.032%	719.4	0.8	3,001	915	3,159,250	0.305	IGL

*Data from this test was not used in fits due to failure occuring at a surface defect.

[a] IGL = Inside gage length
[b] All stress values reported are from mid-life
[c] Load-controlled test was pre-cycled at the OL strain amplitude of 0.350% for 1000 cycles. Damage from the pre-strained cycles is included in the OL damage ratio