Effective Strain-Fatigue Life of Dual Phase 590 Steel

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Abstract

Dual phase 590 steel belongs to the family of advanced high strength steels (AHSS) that has gained popularity in the automotive industry as lightweight vehicle components. An experimental study on dual phase (DP) 590 as-received steel was conducted to study the effect of variable amplitude loading on the fatigue life and construct the effective strain-life curve for the material. Overloads were applied in the form of large near yield stress cycles that decreased the crack opening stress for the subsequent smaller cycles. An effective strain-life curve was derived from constant amplitude and overload tests, and a crack opening stress equation was calibrated by a comparison of constant amplitude and effective strain ranges at given fatigue lives. It was also noticed that the material even at a life of 10^7 cycles exhibited significant plastic strain amplitudes that deviated from the single slope behavior of a Coffin-Manson equation.

1. Introduction

Consumer preferences have limited the downsizing options available to automakers, and regulatory requirements and performance standards have resulted in a very limited ability to reduce weight further with conventional materials [1]. Several new commercialized advanced high-strength steels (AHSS) that exhibit high strength and enhanced formability are being offered in the automotive industry. These steels help optimize crashworthiness and greatly improve both formability and durability [2]. This paper describes an investigation of the fatigue durability of DP 590 steel one of a class of high strength formable steels. Dual phase steels feature a soft ferrite microstructure which is a soft phase and gives a low yield point, and a matrix containing islands of martensite which increases hardenability [3]. Tests are described that produce "effective strain-life" and crack opening stress curves for use in the fatigue analysis of components that experience severe variable amplitude service loads. The effective strain life curve is derived from constant amplitude and overload tests which contain blocks of one large strain cycle and varying numbers of smaller cycles that result in crack closure free crack growth during the small cycles. The calculations of the steady state crack opening stress are based on an empirical model proposed by DuQuesnay [4]. The constants for the crack opening stress equation are obtained by comparing strains at given lives in a constant amplitude strain-life curve with those in the effective strain-life curve.

2. Material and Experimental Methods

2.1 Material

The material used in this study is DP 590 steel in the as-received condition. The chemical composition and mechanical properties of the material are given in Tables 1 and 2 respectively. Specimens are fabricated from DP 590 flat steel sheets 2 mm in thickness. The geometry and dimensions are chosen so that they are adequate to resist buckling (Fig. 1). However for high strain amplitudes (up to the 1% strain level), two specimens are laminated to further increase buckling resistance.

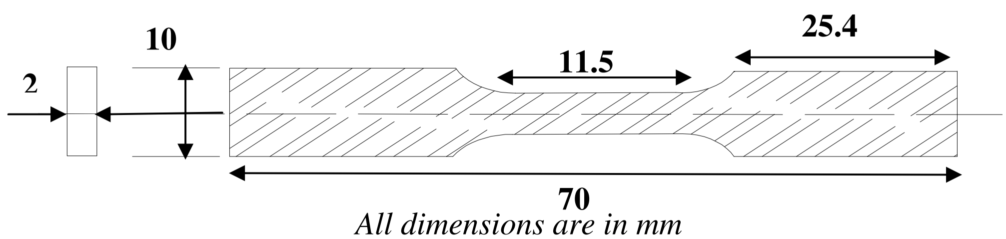

Figure 1 Standard flat sheet specimen geometry

Table 1 Chemical composition of DP 590 steel (percentage by weight)

C	Mn	P	S	Si	Cu	Ni	Cr	Cb	Al	Sn	N
0.09	1.01	0.01	0.01	0.28	<0.02	<0.02	0.02	<0.008	0.04	0.01	0.01

Table 2 Mechanical properties of DP 590 steel

Mechanical properties	**Units**	**Magnitude**
Elastic Modulus, $\boldsymbol{E}$	MPa	200,000
Yield Strength, $\boldsymbol{S_y}$	MPa	349
Ultimate Tensile Strength, $\boldsymbol{S_u}$	MPa	623
% Elongation	%	3.4
% Reduction of Area	%	57
True Fracture Strain, $\boldsymbol{ln}\left(\frac{A_i}{A_f}\right)$	%	84.3
True Fracture Stress, $\sigma_f = \frac{P_f}{A_f}$	MPa	1369
Monotonic Tensile Strength Coefficient, $\boldsymbol{K}$	MPa	730
Monotonic Tensile Strain Hardening Exponent, $\boldsymbol{n}$	-	0.12
Hardness, Rockwell B	-	87

2.2 Constant Amplitude Fatigue Tests

Axial, constant amplitude, fully reversed (R=-1) strain-controlled fatigue tests were performed on DP 590 steel specimens and were used to generate the cyclic stress-strain and the total strain-life curves. Fatigue tests were carried out using an MTS servo-controlled closed loop electro hydraulic testing machine with a process control computer controlled by FLEX software [5] to output constant strain and stress amplitudes in the form of sinusoidal waves. Specimen failure was defined as a 50% drop in the tensile peak load from the peak tensile load observed at one half of the expected specimen life. Stabilized stress data obtained from strain-life fatigue tests were used to construct the companion specimen cyclic stress-strain curve for the DP 590 steel (Fig. 2). The true monotonic and true cyclic stress-strain curves are also shown in Fig. 2. A constant amplitude fatigue life curve is shown in Fig. 3.The four fatigue constants used in constructing the strain-life curve as well as other fatigue properties are represented in Table 3. It is noticed in Fig. 3 that the material exhibit significant plastic strain and strain sensitivity even at long lives (10^7 cycles).The plot of the plastic strain amplitude versus cyclic life reflects a departure from the linearity of the Coffin-Manson relationship. Similar behavior was reported by [6], where they tested 2024-T4 and 7075-T6 aluminum alloys. They related this deviation from single slope behavior of a Coffin-Manson plot to the relative inability of the microstructure to develop homogenous slip during low plastic strain cycling. Due to the significant plastic strains observed and the strain rate sensitivity response of the material, the maximum frequency that didn't result in specimen overheating was 20 Hz.

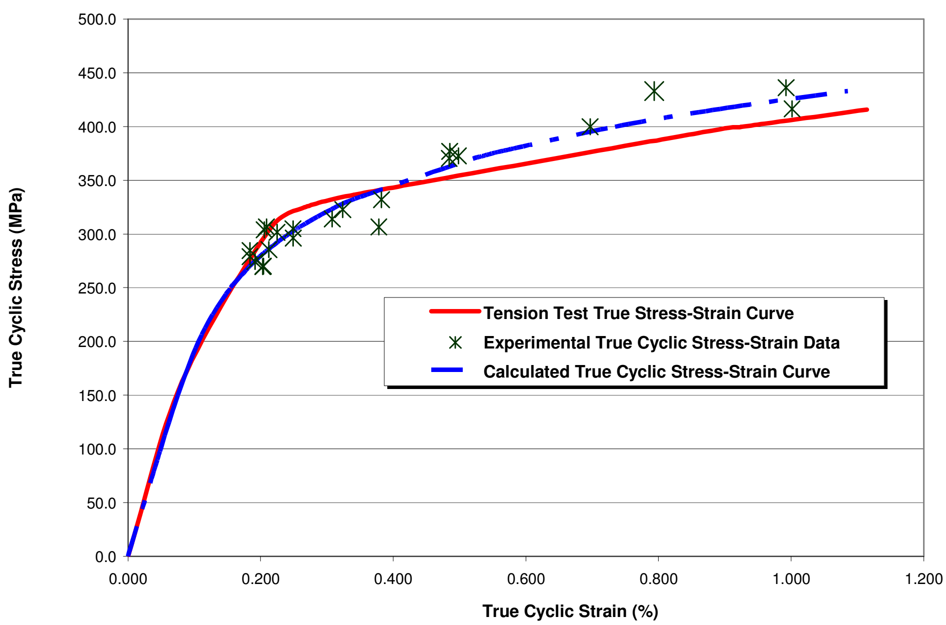

Figure 2 Cyclic stress-strain curve of DP 590 steel

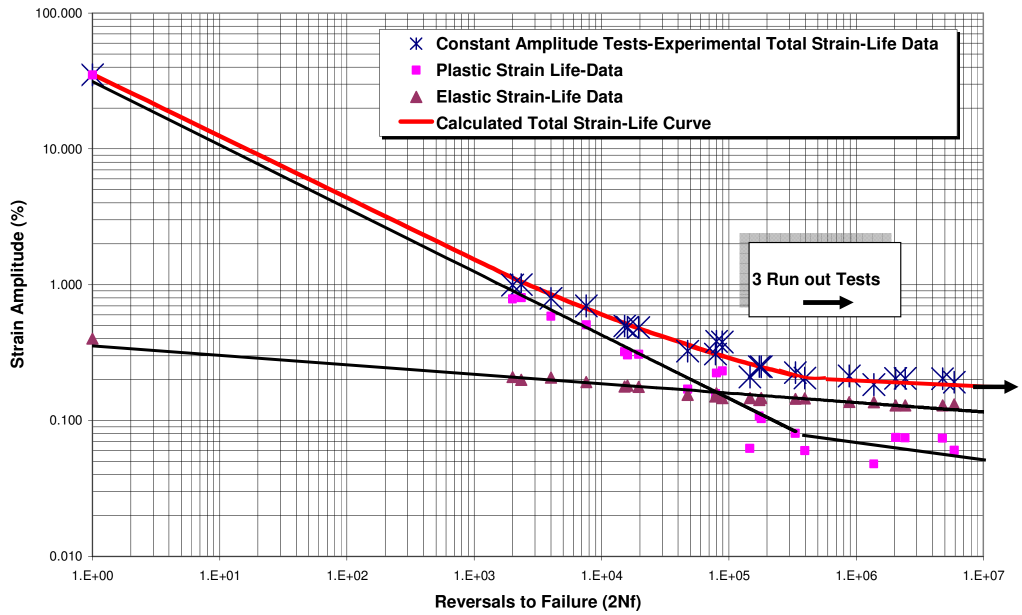

Figure 3 True strain-life curve of DP 590 steel

Table 3 Cyclic properties of DP 590 steel

Cyclic fatigue properties	**Units**	**Magnitude**
Cyclic Yield Strength, (0.2% offset) $= K'(0.002)^{n'}$	MPa	339
Cyclic Strength Coefficient, K'	MPa	949.3
Cyclic Strain Hardening Exponent, n'	-	0.166
Cyclic Elastic Modulus, E_c	MPa	200
Fatigue Strength Coefficient, σ'_f	MPa	733
Fatigue Strength Exponent, b	-	-0.072
Fatigue Ductility Coefficient, ε'_f *	-	0.255
Fatigue Ductility Exponent, c*	-	-0.5

**Fatigue properties obtained from the log-log linear least square fit of data up to 300,000 reversals*

2.3 Overload Fatigue Tests

Fatigue life estimates for structural components subjected to variable amplitude service loading are usually based on the same reference constant amplitude strain-life data that is used for constant amplitude fatigue predictions. The resulting fatigue estimates are always non-conservative for severe variable amplitude load histories. Pervious work at the University of Waterloo introduced an effective strain-life curve for use in fatigue damage calculations [7]. This effective stain-life curve is derived from periodic overload tests consisting of two blocks of load cycles repeated. The first consists of a single overload (tensile and compressive overload peaks) cycle, and this is followed by a block of smaller load cycles that have the same peak stress as the overload cycle. 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 in this paper is set equal to the fully reversed constant-amplitude stress level that will give a fatigue life of 10,000 cycles. The reason for this choice is 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 is chosen so that they did 80 to 90% of the damage to the specimen and that they are free from closure. The damage due to the overloads is removed using Miner's rule [8] and the equivalent failure life of the small cycles in each test is calculated. Overload fatigue data of DP 590 steel specimens are shown in Fig. 4 together with the strain-life curve. The application of overloads have lead to reductions in crack closure during the large cycles in the variable amplitude load history which results in lower crack opening stresses for the small cycles than those in the constant amplitude reference tests used. This increases the effective strain range and the damage done by the small cycles and results in shorter than predicted fatigue lives.

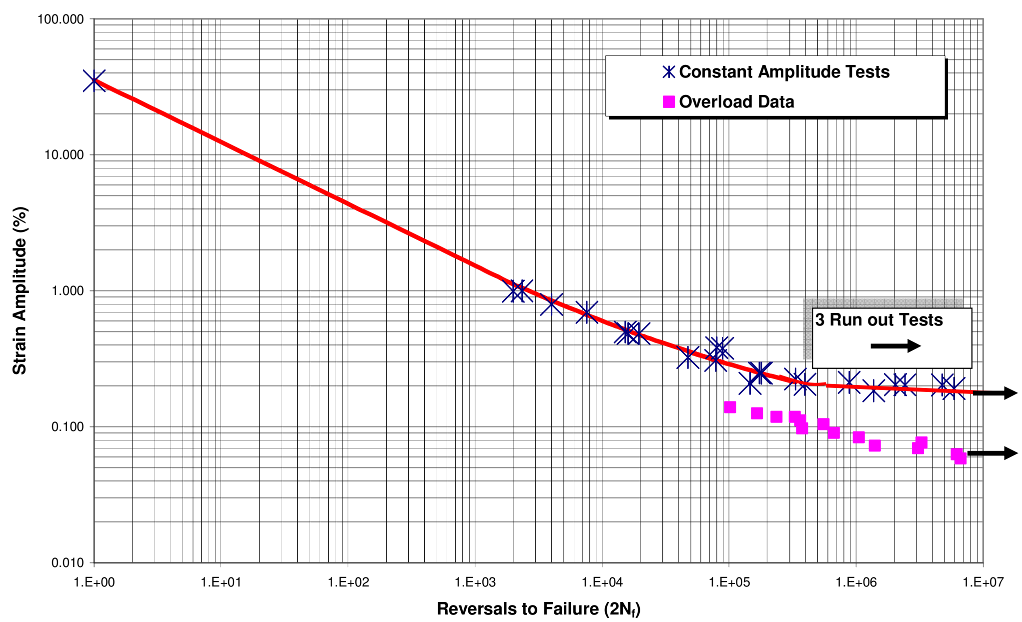

Figure 4 Constant amplitude strain-life curve and overload fatigue data of DP 590 steel

2.4 Calculation of the Effective Strain-Life Curve and the Steady State Crack Opening Stress

When steady state crack opening strain levels for constant amplitude straining are available, the effective strain in a cycle can be calculated directly as the difference between the maximum and the crack opening strain. However measuring the crack opening stresses at the high local stress levels and short crack lengths associated with the growth of short cracks from stress raisers is time consuming. In this investigation an effective strain-life curve was derived from the constant amplitude and overload (effective strain-life) test data of Fig. 4, and a crack opening stress equation was calibrated by a comparison of constant amplitude and effective strain ranges at given fatigue lives.

2.4.1 Calculation of the Effective Strain-Life curve

Referring to the fully reversed constant amplitude and overload test data in Fig. 4, the effective strain range $\Delta\varepsilon_{eff}$ is the part of the total strain range for which a fatigue crack is open during a cycle. It is given as the difference between the maximum strain and the greater of the minimum strain or the crack opening strain. In order to construct the effective strain-life curve, the following damage parameter [9] is used:

$$E\Delta\varepsilon^{*} = E\Delta\varepsilon_{eff} - E\Delta\varepsilon_{i} \qquad \text{(Eq.1)}$$

Where E is the modulus of elasticity and $\Delta\varepsilon_i$ is a material's intrinsic fatigue limit, the strain range below which a fully open crack will not cause fatigue damage. The strain range $\Delta\varepsilon^{*}$ is that part of the total effective strain range which actually causes fatigue crack growth and damage. It is related to the fatigue life by a power law [10]:

$$E\Delta\varepsilon^{*} = AN_f^{b} \qquad \text{(Eq.2)}$$

Where A and b are material constants. Values of *92.1* and *-0.508* were obtained for A and b respectively.

The $E\Delta\varepsilon^{*}$ vs. N_f and the constant $E\Delta\varepsilon_i$ curves were obtained by choosing a value of $E\Delta\varepsilon_i$ which made the $E\Delta\varepsilon^{*}$ vs. N_f curve linear (on log-log coordinates). $\Delta\varepsilon_{eff}$ is the strain range drawn from the small cycle overload test data. For curve fitting purposes, an additional data point was added to the overload curve by calculating the effective strain range assuming that the crack in the 2% strain range constant amplitude test opens at one half the minimum stress. After obtaining $E\Delta\varepsilon_i$ and the values of A and b in Eq. (2), the effective strain life curve is given by Eq. (3):

$$\Delta\varepsilon_{eff} = \frac{A}{E}N_f^{b} + \Delta\varepsilon_{i} \qquad \text{(Eq.3)}$$

2.4.2 Calculation of the Steady State Crack Opening Stress

In addition to the effective strain-life curve, steady state crack opening stresses were determined for the steel. The difference between the strain range at a given fatigue life on a fully reversed constant amplitude life curve $\Delta\varepsilon_{CA}$ and that on the effective strain life curve $\Delta\varepsilon_{eff}$ is equal to the difference between the minimum strain, ε_{min}, and the crack opening strain, ε_{op}, in the constant amplitude stress-strain loop.

$$\Delta\varepsilon_{CA} - \Delta\varepsilon_{eff} = \varepsilon_{op} - \varepsilon_{min} = \frac{(S_{op} - S_{min})}{E} \qquad \text{(Eq.4)}$$

Therefore S_{op} can be written as follows:

$$S_{op} = S_{min} + E(\Delta\varepsilon_{CA} - \Delta\varepsilon_{eff}) \qquad \text{(Eq.5)}$$

The values of S_{op} are then used to obtain the constants in the model for the steady state crack opening stress under constant amplitude loading proposed by DuQuesnay [4] and is given by Eq. (6) as follows:

$$S_{op} = \theta\sigma_{max}\left[1 - \left(\frac{\sigma_{max}}{\sigma_y}\right)\right] + \varphi\sigma_{min} \qquad \text{(Eq.6)}$$

Where σ_{max} and σ_{min} are the nominal maximum and minimum stresses in a smooth specimen, respectively, σ_y is the cyclic yield stress, and θ and φ are constants determined by fitting Eq. (6) to the calculated S_{op} data. Values of *0.9* and *0.05* were obtained for θ and φ respectively. The value of S_y used for this material was 430 MPa. The effective strain-life curve as well as the crack opening stress data are shown in Figs. 5 and 6. It is noticed in Fig. 6 that the steady state crack opening stress initially increases linearly when the maximum stress in a cycle is increased, it then levels off at about one half of the material yield stress and then decreases until it falls below zero when the plastic zone at the crack tip expands rapidly as the metal yield stress is approached.

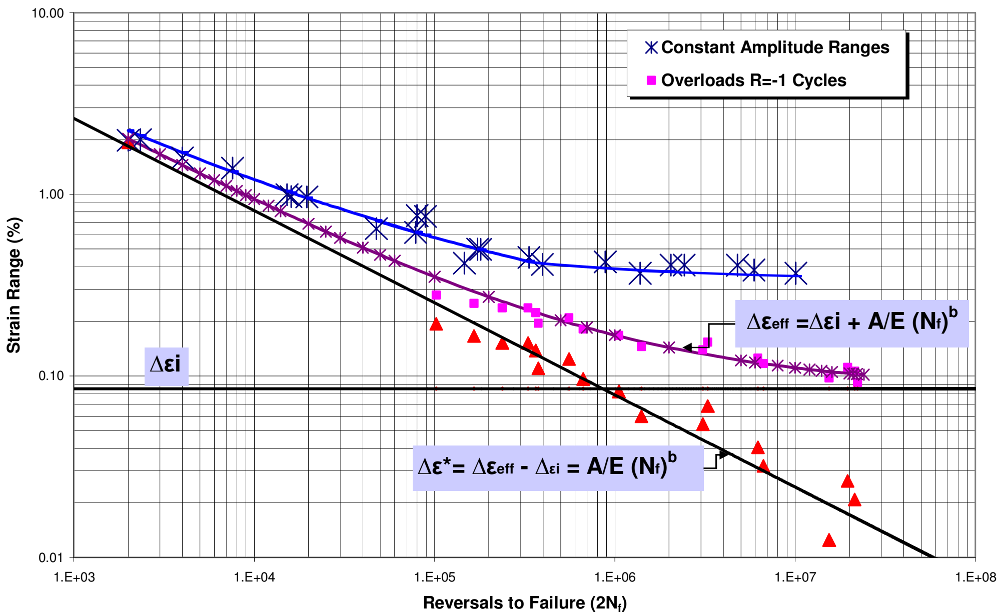

Figure 5 Fully reversed constant amplitude fatigue data and the effective strain life curve of DP 590 steel

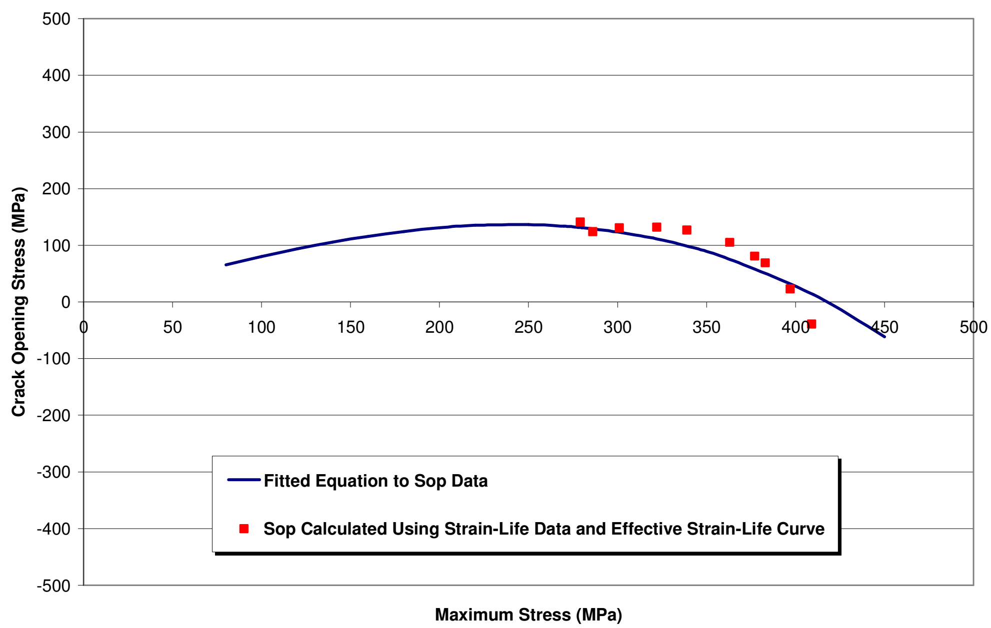

Figure 6 Crack opening stress data of DP 590 steel fitted to Eq. (6)

3 Conclusions

The effective strain-life curve was constructed for DP 590 steel from fully reversed constant amplitude strain tests and overload tests. The variable amplitude loading was characterized by using the steady state crack opening stress model proposed by DuQuesnay [4].From the results of the tests of the DP 590 steel, reported in this paper, the following conclusions are drawn:

i) For this steel the plastic strain-life curve deviated from the normal logarithmic decrease of plastic strain range with fatigue life and continued to exhibit significant plastic strains and a strain rate sensitivity even at a life of 10^{7} cycles.

ii) The material showed a significant amount of plastic strain and frequency response even at long fatigue lives. The maximum frequency that did not result in specimen overheating was 20 Hz.

iii) The test procedure suggested gave a good effective strain-life data and a reasonable estimate of steady state crack opening stresses with a reasonable amount of testing. Use of the equations provides a simplified standard fitting procedure that is simple to apply. It has been shown to give good results in providing crack opening stress estimates and produce a smooth crack opening stress curve.

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