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Modeling of Crack-Opening Stress Levels under Different Service Loading Spectra and Stress Levels for a 1045 Annealed Steel

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ABSTRACT

The crack opening stresses of a crack emanating from an edge notch in a 1045 annealed steel specimen were measured under three different Society of Automotive Engineers (SAE) standard service load histories having different average mean stress levels. The three spectra are the SAE Grapple Skidder history (GSH) which has a positive average mean stress, the Log Skidder history (LSH) which has a zero average mean stress, and the Inverse of the GSH (IGSH) which has a negative average mean stress. In order to capture the actual behavior of the crack opening stress in the material, the crack opening stress levels were measured using a 900X optical video microscope at frequent intervals for each set of histories scaled to two different maximum stress ranges.

The crack opening stresses were modeled assuming that the crack opening stress when it is not at the constant amplitude steady state level for a given stress cycle builds up as an exponential function of the difference between the current crack opening stress and the steady state crack opening stress of the given cycle unless this cycle is below the intrinsic stress range for crack growth or the maximum stress in the cycle is below zero in which case the crack opening stress does not change.

The crack opening stress model was implemented in a fatigue notch model and the fatigue lives of notched annealed 1045 steel specimens under the three different spectra scaled to several maximum stress levels were estimated. The average measured crack opening stresses were within between 8 and 13 percent of the average calculated crack opening stresses. The fatigue life predictions based on the modeled crack opening stresses and the fatigue notch model were in good agreement with the experimentally determined fatigue data.

KEYWORDS

Service spectrum – Crack-opening stress – Effective strain intensity factor – Steady state crack-opening stress.

INTRODUCTION

An empirical model for the steady state crack opening stress S_{op} under constant amplitude loading by DuQuesnay [*1*] gave good predictions of measured crack opening stress levels. Many researchers have documented the effects of variable amplitude loading on crack closure [*2-8*]. The application of a tensile overload can cause either an acceleration or a delay in crack growth. A post overload increase in crack closure level and crack growth retardation occurs when the applied overload is less than approximately one half the yield stress of the material [6, *9, 10,*]. An overload of much more than one half the yield stress of the material will decrease the crack closure level and accelerate crack growth. Applying an underload causes a flattening of the asperities in the crack wake, which decreases the crack closure level and in turn increases the effective stress intensity factor and accelerates crack propagation.

This research is aimed at providing crack closure inputs for modeling fatigue damage or crack growth in a specimen under service loading spectra. The crack opening stress behavior of cracked specimens under service loading spectra is modeled and the accuracy of the model is evaluated experimentally using measured crack closure data. This paper is a continuation to research previously presented by the authors [*11*] using the same load spectra in tests on a 2024-T351 aluminum alloy.

MATERIAL AND EXPERIMENTAL METHODS

The material used in this study is a SAE 1045 as received steel which is commonly used in the automotive industry. The chemical composition and mechanical properties of the material are given in Tables 1 and 2 respectively. All testing was carried out on round threaded specimens with a rectangular gauge length profile. The geometry and dimensions are shown in Figure 1. An edge notch of 0.6 mm diameter was machined into one side of the specimen, at mid length as shown in (Figure 1). Using a notched specimen allows the stresses to exceed the material yield stress at the notch root without buckling or tensile yielding of the whole specimen. This notch size was small enough that, once initiated, the crack rapidly grew out of the zone of influence of the notch.

The crack opening stress was measured using a 900x power short focal length optical video microscope at given cycles before and after an overload occurred. The procedure for measuring the crack opening stress was to stop the test at the maximum stress of the required cycle and then to decrease the load manually while observing the crack tip region in the monitor attached to the optical video until the crack surfaces start to touch each other. Two sets of readings were recorded for each given cyclic stress level, and the average were calculated.

Table 1 – Chemical Composition (percentage by weight)

Steel	C	Si	P	Mn	S	Fe
1045	0.46	0.17	0.027	0.81	0.023	rest

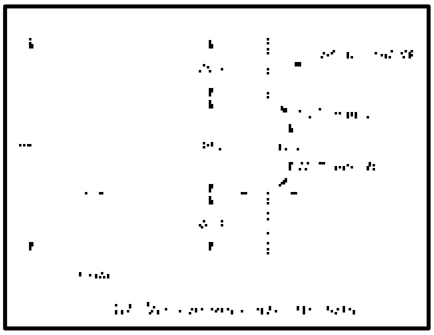

Figure 1 Specimen Geometry

Table 2 – Mechanical Properties of 1045 As-Received Steel

Mechanical Properties	Units	Magnitude
Modulus of Elasticity	MPa	206000
Tensile Yield Stress (0.2% offset)	MPa	761
Cyclic Yield Stress (0.2% offset)	MPa	580
Ultimate Tensile Stress	MPa	781
True Fracture Stress	MPa	647
Area Reduction	%	40

Crack opening stress model

Dabayeh and Topper [*12*] measured crack opening stress changes for various levels of tensile and compressive overloads followed by constant amplitude cycles having a variety of R-ratios.

The crack opening stress after being reduced by the overload increased to its steady state level in an approximately exponential manner. They showed that when normalized all the closure stress versus cycles, data fell onto a single curve. However, the application of their relationship to complex load histories is complicated. The present authors have applied a simpler relationship suggested by Vormwald and Seeger [13] relating the change in crack opening stress in a given cycle to the difference between the current opening stress S_{cu} and the steady state opening stress S_{ss}.

$$\Delta S_{op} = m(S_{ss} - S_{cu}) \qquad (1)$$

where ΔS_{op} is the increase in crack opening stress during a load cycle and m is a material constant produced by fitting equation (1) to crack-opening stress build-up measurements. A value of m equal to 0.002 gives a good fit to the measured crack-opening stress data. The constants for DuQuesnay's steady state crack opening stress model were calibrated by measuring crack opening stress during a load history consisting of different maximum and minimum stresses. The two constants were found to be 0.55 and 0.23 for $\boldsymbol{a}$ and $\boldsymbol{b}$ respectively.

Using equation 1 the crack-opening stress levels were modeled assuming that the crack-opening stress for a given cycle instantaneously decreases to the constant amplitude steady state level for that cycle if this steady state crack opening stress is lower than the current opening stress. Otherwise it follows the exponential build-up formula of equation 1 unless the cycle is below the intrinsic stress range, or the maximum stress is below zero in which case it doesn't change.

Crack growth analysis

A crack growth analysis based on a fracture mechanics approach as presented by Dabayeh et al. [14] was used to model the fatigue behavior of the 1045 as received steel specimens for the given load spectra and stress ranges. The crack growth analysis was based on an effective strain-based intensity factor as presented by Dabayeh et al. [14], a crack growth rate curve obtained during closure-free loading cycles, and a local notch strain calculation based on Neuber's rule [14].

Experimental measurements

The three load spectra were scaled to various maximum stress ranges. The upper limit of these ranges was set so the maximum and minimum stresses did not cause large scale notch plasticity as the fatigue crack grew out of the notch while the lower limit was set so that fatigue lives did not exceed fifteen hundred blocks. In order to obtain the fatigue life curves the three spectra mentioned above were scaled to various stress ranges and applied to the 1045 notched steel specimens till failure.

Results for the SAE Grapple Skidder Load History

For the experimental crack closure measurements the torsion channel of the Grapple Skidder spectrum which has a positive mean stress was scaled to two different stress levels, a maximum nominal stress range of 910 MPa and a maximum nominal stress range of 751 MPa. The measured crack opening stresses for the two different maximum stress levels are shown in Figures 2 and 3 respectively. The figures show the applied nominal stress spectrum for each load history, the calculated crack opening stresses using the crack opening stress model and the experimentally measured crack opening stresses. Figure 4 is an expanded view of a portion of Figure 2 that shows the modeled and experimental crack opening stress. As expected, the crack opening stress decreases when the specimen is subjected to a large overload then starts to build-up again during subsequent smaller cycles. The average measured crack opening stresses were within 8 and 9 percent of the average calculated crack opening stresses for the two different maximum stress levels. Figure 5 shows a plot of the measured fatigue lives versus the maximum stress range of the Grapple Skidder load spectrum and the lives predicted using the crack opening stress model in the fatigue crack growth program. The estimated fatigue lives are in good agreement with the experimental observations.

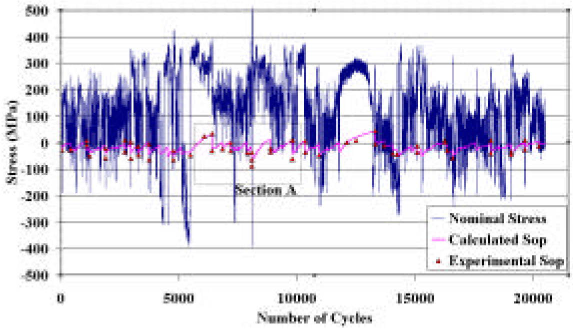

Figure 2. GSH Maximum Stress 910 MPa

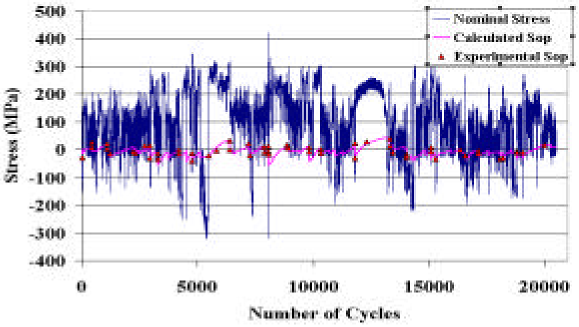

Figure 3. GSH Maximum Stress 751 MPa

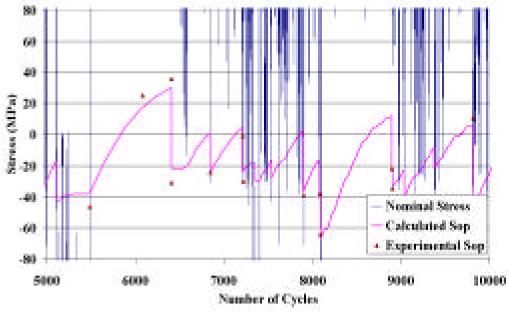

Figure 4. Section A

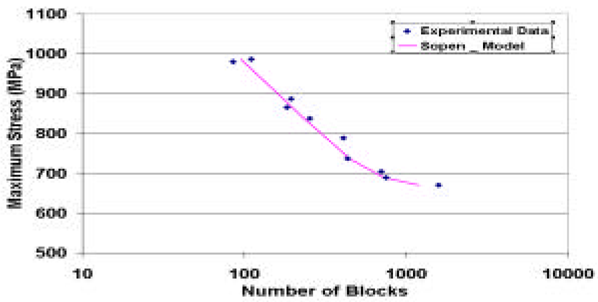

Figure 5. Fatigue Life vs. maximum stress (GSH)

Results for the SAE Log Skidder Load History

The cable channel of the Log Skidder spectrum which had an average mean stress of zero was scaled to two different stress levels. These stress levels were: a maximum nominal stress range of 887 MPa and a maximum nominal stress range of 675 MPa. The crack opening stresses for the maximum stress ranges are shown in Figures 6 and 7 respectively. The figures show the nominal applied spectrum for maximum stress ranges of 887 MPa and 675 MPa, the calculated crack opening stresses using the crack opening stress model and the experimentally measured crack opening stresses. Figure 8 is an expanded view of a portion of Figure 6 that shows the modeled and experimental crack opening stress. The average measured crack opening stress were within 9 and 11 percent of the average calculated crack opening stress for the two different maximum stress levels respectively. Figure 9 shows the measured fatigue lives versus the maximum stress range of the Log Skidder load Spectrum. The estimated fatigue lives are in good agreement with the experimental values.

Results for the Inverse Grapple Skidder Load History

The inverse of the torsion channel of the Grapple Skidder spectrum which had a negative mean stress was scaled to two different maximum stress levels. These stress levels are: A maximum nominal stress range of 1008 MPa and a maximum nominal stress range of 675 MPa. The crack opening stresses for the two maximum stress ranges are shown in Figures 10 and 11 respectively. Figure 12 is an expanded view of portion of Figure 7 that shows the modeled and experimental crack opening stress. The average measured crack opening stresses were within 13 and 10 percent of the average calculated crack opening stress for the two different maximum stresses levels respectively. Figure 13 shows the measured fatigue lives versus the maximum stress range of the inverse Grapple Skidder Spectrum. The estimated fatigue lives are in good agreement with the experimental values.

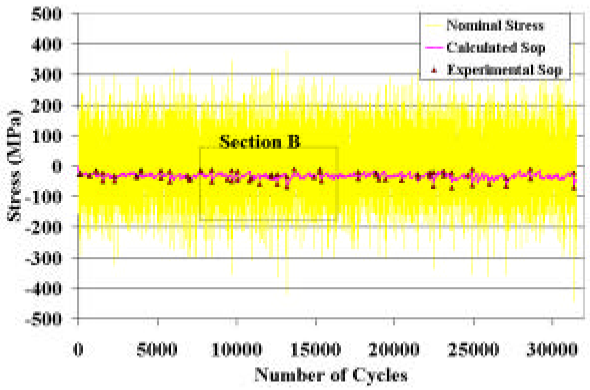

Figure 6. LSH Maximum Stress 887 Mpa

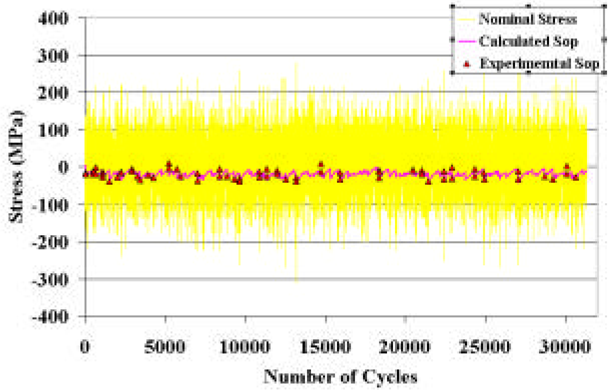

Figure 7. LSH Maximum Stress 675 MPa

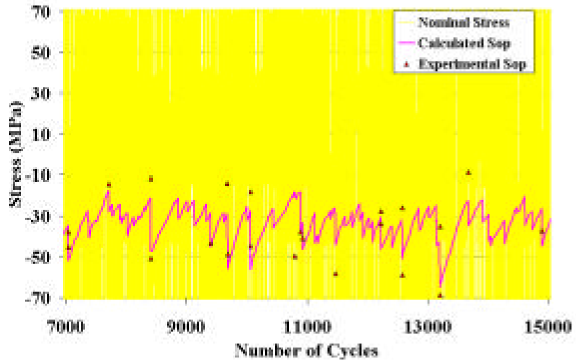

Figure 8. Section B

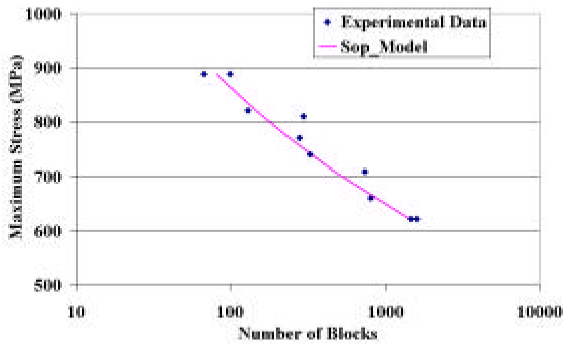

Figure 9. Fatigue Life vs. maximum stress (LSH)

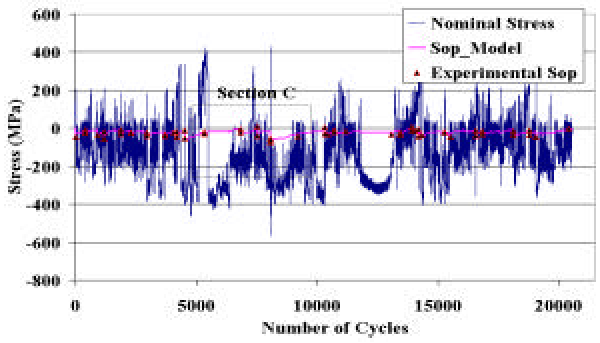

Figure 10. IGSH Maximum Stress 1008 Mpa

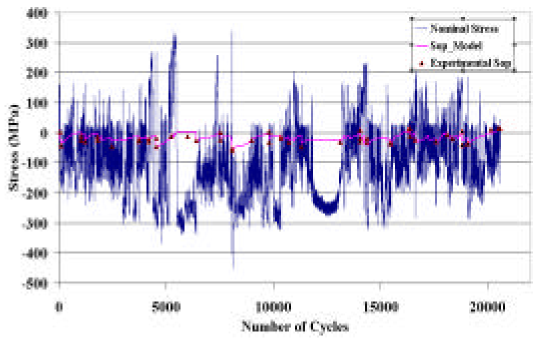

Figure 11. IGSH Maximum Stress 675 MPa

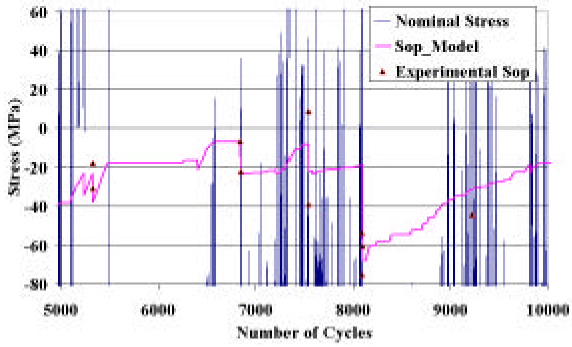

Figure 12. Section C

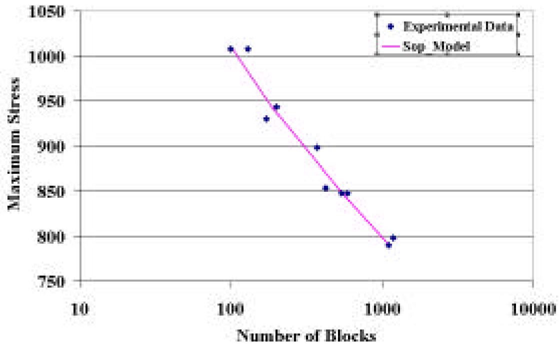

Figure 13. Fatigue Life vs. maximum stress (IGSH)

CONCLUSIONS

1. The crack-opening stress level dropped immediately after the application of an overload and then gradually increased with subsequent small cycles.
2. The crack opening stress can be modeled using an exponential build-up formula which is a function of the difference between the current crack opening stress and the steady state crack opening stress of the given cycle.

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