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A model of crack opening stresses in variable amplitude loading using smooth specimen fatigue test data for three steels

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ABSTRACT

Crack growth under variable amplitude loading can be largely explained through changes in fatigue crack closure and crack opening stress. This paper presents a methodology for modeling changes in crack opening stress level and fatigue damage using data derived from periodic underload fatigue tests of smooth specimens for three steels with diverse hardness (soft, medium, and hard). The predicted crack closure stress levels are modeled under constant and variable amplitude loading (SAE Log Skidder History) and agree well with experimental measurements made with a high magnification microscope.

1. Introduction

For many years, constant amplitude data obtained from smooth specimens has been used to evaluate the fatigue life of components. Unfortunately, such data turned out to be unreliable and non-conservative for predicting variable amplitude fatigue behavior for both smooth laboratory specimens and components in service. These non-conservative predictions have, in both cases, been shown to be due to severe reductions in fatigue crack closure arising from large (overload or underload) cycles in a typical service load history. Smaller load cycles following a large near yield stress overload or underload cycle experience a much lower crack opening stress than that experienced by the same cycles in the reference constant amplitude fatigue tests used to produce design data. This reduced crack opening stress (due to the overload or underload cycle) results in the crack remaining open for a larger fraction of the stress–strain cycle and thus an increase in the effective portion of the stress–strain cycle. Therefore, the effective strain range (the strain range for which the crack is fully open) is increased and the fatigue damage for the small cycles following the overload or underload cycle is greater than that calculated from constant amplitude data resulting in a non-conservative fatigue life prediction. It is the objective of this study to model these changes of the crack opening stresses after the application of underloads using smooth specimen test data and replace the current time consuming tests in which crack opening stress recovery is measured directly for crack growth specimens. Another aim of this study is to relate the parameters for the crack opening levels with material cyclic deformation resistance, which in turn increases with hardness. Further information regarding this relationship has been obtained in this study by testing different steels (Dual Phase 590, SAE 1045, and AISI 8822) of varying hardness levels including a very hard carburized steel (AISI 8822) having a hardness level for which no crack opening stress data for small cracks had yet been obtained. The work in this investigation included fully reversed constant amplitude fatigue tests, underload fatigue tests, crack opening stress and crack opening stress build-up measurements made under different stress ratios (*R*-ratio), damage tests and service load history tests.

1.1. Crack opening stress under constant amplitude loading (steady state crack opening stresses)

A steady state condition of crack closure is reached when the residual plastic deformations and crack closure along the crack surfaces are fully developed and stabilized under steady state loading (or constant amplitude loading) [1]. A number of researchers have provided analytical or finite element solutions for steady state crack closure at high stresses [2]. McEvily and Minakawa [3] showed that for a crack propagating under constant amplitude loading, closure builds-up to a steady state level within several hundred microns of growth, and it remains at this level for most of the fatigue life. Newman [4] developed crack opening stress

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equations for constant amplitude loading from crack closure model calculations for a middle-crack tension specimen. His model proposed an analytical formulation based on the Dugdale model but modified to leave plastically deformed material in the wake of the advancing crack tip. However in this investigation the steady state crack opening stresses were modeled using Eq. (1) proposed by DuQuesnay et al. [5] that relates the steady state crack opening stresses under constant amplitude loading to the maximum and minimum stresses applied:

$$S_{opss} = \theta\sigma_{\max}\left[1 - \left(\frac{\sigma_{\max}}{\sigma_y}\right)^2\right] + \varphi\sigma_{\min} \tag{1}$$

where S_{opss} is the steady state crack opening stress under constant amplitude loading, $\sigma_{\max}$ and $\sigma_{\min}$ are the nominal maximum and minimum stresses in a smooth specimen, or the local maximum and minimum stresses at the notch root in a notched specimen respectively. σ_y is the cyclic yield stress, and θ and φ are two experimentally determined constants for a material. The first constant θ is related to the height of the stretched material (plastic zone size) in the crack wake compared to the crack opening displacement, and the second constant φ is related to the reduction of the stretch by the minimum stress.

1.2. Crack opening stress under variable amplitude loading

In the early 1960s, load interaction effects were first recognized [6,7]. The application of a single over load was observed to cause a decrease in the crack growth rate. This phenomenon is termed as crack retardation. A tensile overload in a constant amplitude fatigue test will result in an increase in the plastic zone size and the tensile stretch in front of the crack tip as compared to the baseline cyclic loading. The plastically deformed material ahead of the crack tip will tend to keep the crack open causing a decrease in the crack opening stress magnitude, S_{op}. This will then result in an increased crack growth rate. When the tensile overload is less than about one half of the yield stress when the crack grows into the overload plastic zone, the stretched material will increase the height of the plastic wake and the crack opening stress and decrease the effective stress range and the effective stress intensity factor and the crack growth rate will decrease. As the magnitude of the tensile overload increases on the other hand, the magnitude of the plastic zone increases to such an extent that the stresses in the elastic zone no longer exert a sufficient clamping force on the stretched zone to cause an increase in the crack opening stress to an above steady state level and there ceases to be a decrease in the crack growth rate to a below steady state level. Instead of a period decreased crack growth rate, the crack growth rate decreases asymptotically to the steady state crack growth rate. Compressive near yield limit underloads reduce the crack opening stress and until it recovers to its steady state level, crack growth is accelerated [8]. Varvani and Topper [9] showed that the application of a compressive near yield limit underload contributed to a flattening of the asperities in the crack wake that are responsible for roughness induced crack closure and accelerated crack growth. Dabayeh [10] proposed an empirical formula to simulate the build-up of crack opening stress after an underload in terms of the ratio of the difference between the instantaneous crack opening stress of the small cycles (S_{op}) in the loading block history and the post overload crack opening stress level (S_{opol}), and the difference between the steady state crack opening stress of the small cycles (S_{opss}) and the post overload crack opening stress level:

$$\frac{(S_{op} - S_{opol})}{(S_{opss} - S_{opol})} = 1 - \psi\ \mathrm{Exp}(-b(N/N_{0.8})^{\alpha}) \tag{2}$$

where ψ, b, and a are material constants, N is the number of cycles following the overload, $N_{0.8}$ is the number of cycles following the overload at which the normalized recovered stress $(S_{op} - S_{opol})/(S_{opss} - S_{opol})$ reaches 80% of its steady-state level. However, Khalil and Topper [11] found that the application of Dabayeh [10] formula to complex load histories was complicated. They suggested the use of a simpler model initially proposed by Vormwald and Seeger [12] which relates the change in the crack opening stress in a given cycle to the difference between the current crack opening stress S_{cu} and the steady state crack opening stress S_{opss} in the form of:

$$\Delta S_{op} = m(S_{opss} - S_{cu}) \tag{3}$$

where ΔS_{op} is the change in the crack opening stress, S_{opss} is the steady state crack opening stress, S_{cu} is the current crack opening stress, and m is a material constant obtained in this paper through a series of damage tests that will be discussed in Section 3.4. Previously the material constant m had been derived from direct measurements of crack opening stresses [13]. The equation above describes the crack opening stress build-up after the application of an underload to its steady state condition and was adopted in this study.

1.3. The effective strain-life curve

The effective strain-life curve was generated through a series of underload fatigue tests described in Section 3.2. The effective strain-life curve served several purposes including:

1. Calculating fatigue lives under a variable amplitude loading history (underload tests).
2. Calculating the steady state crack opening stresses and calibrating the constants in Eq. (1).

1.3.1. Constructing the effective strain-life curve

In order to construct the effective strain-life curve a series of underload fatigue tests were performed. The aim of these tests was to keep the crack opening stress under the minimum stress of the small cycles through maintaining a high maximum stress and the frequent application of a compressive near yield limit underload so that we would have fully effective small cycles free from crack closure. The effective strain range is the range of a strain for which a fatigue crack is open during a cycle, and it is given as the difference between the maximum strain and the greater of the crack opening strain or the minimum strain in a cycle. Previous work by Topper and Lam [14] introduced a damage parameter given by:

$$E\Delta\varepsilon^{*} = E\Delta\varepsilon_{eff} - E\Delta\varepsilon_i \tag{4}$$

where E is the elastic modulus of elasticity and $\Delta\varepsilon_i$ is a material's intrinsic fatigue limit strain range below which a fully open crack will not cause fatigue damage. The strain range $\Delta\varepsilon^{*}$ is the part of the strain range which causes fatigue crack growth and damage. This parameter was found to be related to the fatigue life by a power law [15]:

$$E\Delta\varepsilon^{*} = A(N_f)^b \tag{5}$$

where A and b are material constants determined from underload fatigue tests.

The $E\Delta\varepsilon_i$ *vs.* N_f and the $E\Delta\varepsilon^{*}$ *vs.* N_f curves were obtained by choosing a value of $E\Delta\varepsilon_i$ which made the curve of $E\Delta\varepsilon^{*}$ values (calculated from Eq. (4)) *vs.* N_f linear on logarithmic scale. In this process $\Delta\varepsilon_{eff}$ was the strain range of the small cycles in an underload test. For curve fitting purposes, an additional data point was added to the underload curve (based on prior experimental observations) by calculating the effective strain range at a 2% total strain range