

Derivation of Effective Strain-Life Data, Crack Closure Parameters and Effective Crack Growth Data from Smooth Specimen Fatigue Tests

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ABSTRACT

Small crack growth from notches under variable amplitude loading requires that crack opening stress be followed on a cycle by cycle basis and taken into account in making fatigue life predictions. The use of constant amplitude fatigue life data that ignores changes in crack opening stress due to high stress overloads in variable amplitude fatigue leads to non-conservative fatigue life predictions. Similarly fatigue life predictions based on small crack growth calculations for cracks growing from flaws in notches are non-conservative when constant amplitude crack growth data are used. 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. The work in this paper is concerned with the derivation of crack closure constants for use in two models; the effective strain-life fatigue model that can be applied to predict fatigue lives for smooth and blunt notched specimens under constant and variable amplitude loading and the effective fatigue crack growth model that can be used to predict fatigue lives of short cracks growing out of notches or flaws under constant and variable amplitude loading. Fatigue life calculations based on equations using crack opening stress are shown to give accurate fatigue life predictions for smooth and notched specimens subjected to variable amplitude service load histories. The influence of metal hardness on crack opening stress behaviour is deduced by comparing data for the three metal hardness levels used in this investigation.

KEYWORDS: Crack Closure, Variable Amplitude Loading, Crack Opening Stress, Effective Strain-Life Curve, Effective Stress Intensity Factor Range, Fatigue Life Prediction

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INTRODUCTION

Constant amplitude data obtained from smooth specimen constant amplitude fatigue tests is still used to evaluate the fatigue life of components. However this data has 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 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. The effective strain range is increased and the fatigue damage for the small cycles is greater than that calculated resulting in a non-conservative fatigue life predictions.

Since the early 1960's, reduced crack growth rates termed delays have been known to occur after tensile overloads less



than one half the yield stress. Figure 1 shows the trends in crack growth following tensile overloads below about one half the yield stress and for larger tensile and compressive overloads. Referring to Figure 1, 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. 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. However as the magnitude of the tensile overload increases beyond about one half the yield stress, the magnitude of the plastic zone increases to such an extent that the stresses in the remaining 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. Instead 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}) and an increase in the effective stress range and the crack growth rate. After the overload induced increase 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 as shown in Figure 1.

Varvani and Topper [1] showed that the application of an underload in the absence of a prior overload mainly contributes to the flattening of the asperities in the crack wake that are responsible for roughness-induced crack closure and accelerated crack growth. Figure 2 taken from reference [2] shows the elevated crack growth rate that occurs after an underload and its return to a steady state level as cycling progresses. The interval of constant growth rate after the underload corresponds to the constant effective stress range period while the crack opening stress is below the minimum stress in the stress cycle.

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 on 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 (DP) 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.

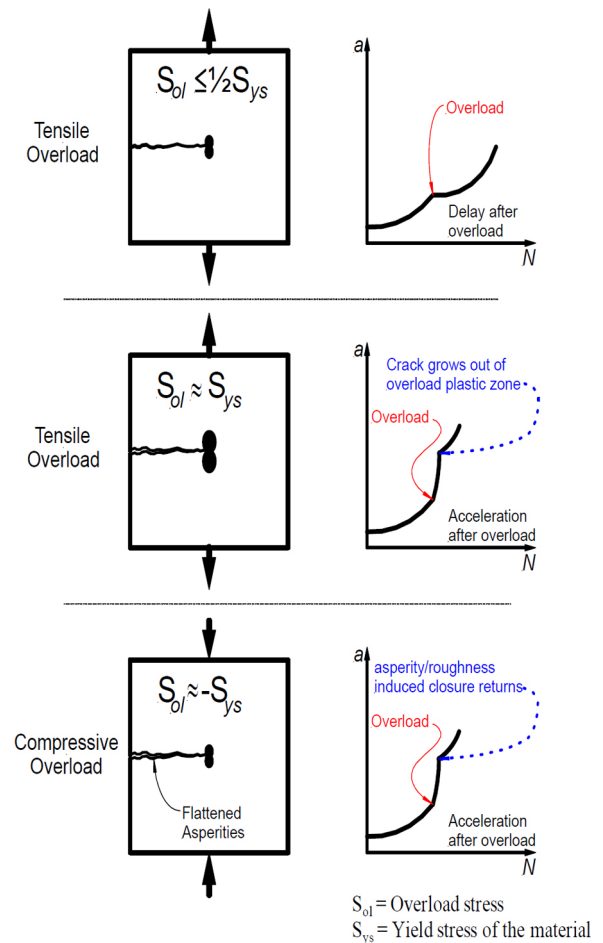


Figure 1. Crack growth rates after tensile and compressive overloads

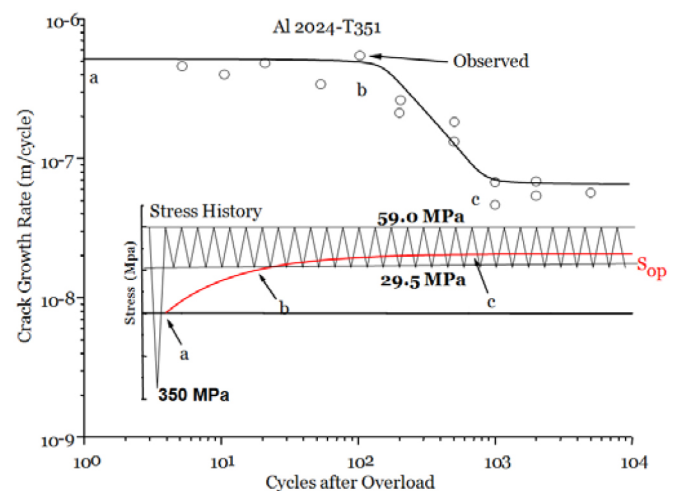


Figure 2. Changes in crack opening stress and crack growth rate following an underload in 2024-T351 Al-alloy

CRACK OPENING STRESS UNDER CONSTANT AMPLITUDE LOADING (STEADY STATE CRACK OPENING STRESSES)

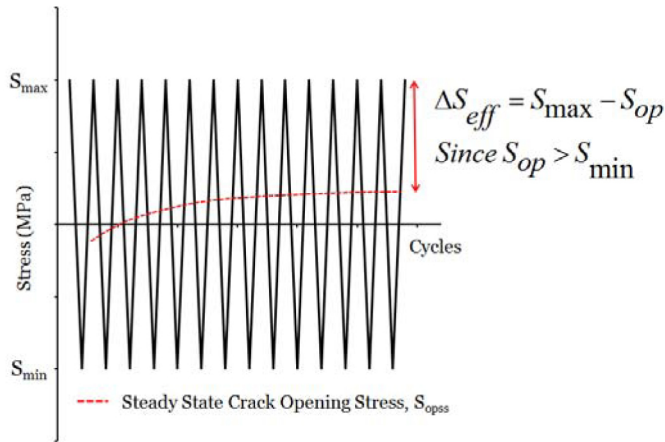


Figure 3. Crack opening stress under constant amplitude loading

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). The trend in crack closure build-up at the start of a constant amplitude fatigue test is shown in Figure 3. A number of researchers have provided analytical or finite element solutions for steady state crack closure at high stresses. McEvily and Minakawa [3] showed that for a crack propagating under constant amplitude loading, closure build-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 equation 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 Equation (1) proposed by DuQuesnay [5] that related the steady state crack opening stresses under constant amplitude loading to the maximum loading and minimum stresses applied:

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

Where S_{opss} is the steady state crack opening stress under constant amplitude loading, σ_{max} and σ_{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 the materials used. 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 flattening of the crack wake.

CRACK OPENING STRESS UNDER VARIABLE AMPLITUDE LOADING

Figure 4 shows the sudden decrease of the crack opening stress after an underload and its return to the steady state level characteristic of a constant amplitude level of smaller cycles. In this study this post underload build-up of the crack opening stress will be described by a simple model initially proposed by Vormwald and Seeger [6] 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:

$$\Delta S_{op} = m(S_{opss} - S_{cu}) \quad (2)$$

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 ” (the crack closure build-up parameter) is a material constant obtained in this paper through a series of damage tests that will be discussed in later section. Previously the material constant “ m ” had been derived from direct measurements of crack opening stresses [7].

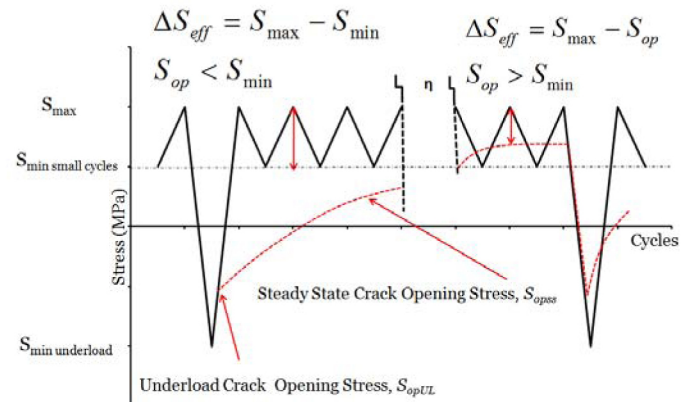


Figure 4. Crack opening stress under variable amplitude loading

MATERIALS

The materials used in this investigation are Dual Phase DP 590 steel, SAE 1045 medium carbon steel and AISI 8822 carburized case steel. DP 590 steel belongs to the family of advanced high strength steels (AHSS) that has been introduced and gradually adopted in vehicle structures as lightweight materials. In general AHSS exhibit higher

ultimate strength than the previously used low carbon steels and therefore thinner sections can be used in vehicle construction to result in same or better quality of the final part while reducing the weight. SAE 1045 steel is used extensively by all industry sectors for applications requiring strength and wear resistance with typical applications including: axles, bolts, connecting rods, hydraulic clamps and rams, shafts, and spindles. AISI 8822 is a nickel-chromium-molybdenum carburizing steel of fairly high hardenability. In components it has high core strength and durable carburized case steel making it suitable for many heavy-duty applications such as shafts and gears. The mechanical properties (monotonic and cyclic properties) as determined in this study for the 3 tested steels are shown in Table 1. DP 590 specimens were fabricated from flat steel sheets 2 mm in thickness and dimensions were chosen so that they were adequate to resist buckling during specimen testing. In addition the radius of the sample was continuously varied decreasing from infinity in a shape determined by finite element calculations to give a stress concentration of less than 1%. SAE 1045 and AISI 8822 smooth, cylindrical gauge length specimens were prepared in accordance with ASTM standard E606 - 04 from 19.05 mm diameter hot rolled bars with the loading axis of each specimen parallel to the direction of rolling. In addition, threaded specimens were fabricated from SAE 1045 steel bars. The round threaded notched specimens with a flat gauge length profile were fabricated for use in crack growth rate tests and crack opening stress measurements. Figure 5 shows the dimensions of the steel specimens tested.

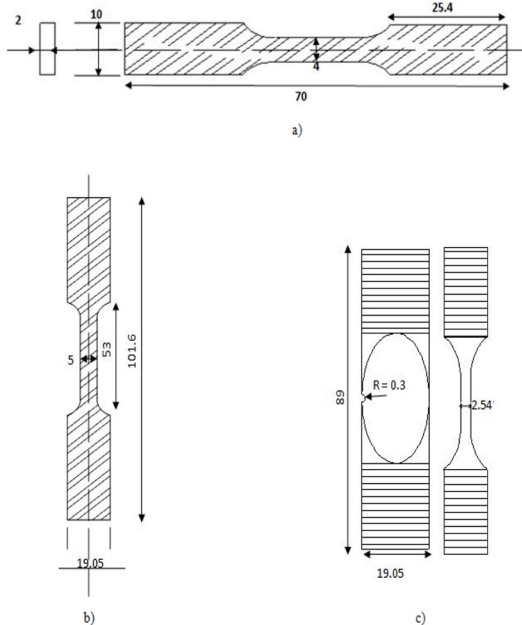


Figure 5. Specimen geometries (all dimensions are in mm): a) DP 590 specimen geometry b) SAE 1045 and AISI 8822 smooth specimen geometry c) SAE 1045 notched crack growth steel specimens

Table 1. Mechanical (monotonic and cyclic) properties of DP590, SAE 1045 and AISI 8822 steels

Mechanical Properties	Units	DP 590	SAE 1045	AISI 8822
Elastic Modulus, E	GPa	209	205	209
Yield Strength, S_y	MPa	349	1200	-
Ultimate Tensile Strength, S_u	MPa	623	1271	1480
True Fracture Stress, σ_f	MPa	743	1879	1480
True Fracture Strain	%	76	56	0.87
% Elongation	%	34	14	0.87
% Reduction of Area	%	53	43	-
Monotonic Tensile Strength Coefficient, K	MPa	730	1470	-
Monotonic Tensile Strain Hardening Exponent, n		0.12	0.033	-
Cyclic Yield Strength, (0.2% offset) = $K'(0.002)^{n'}$	MPa	338	767	-
Cyclic Strength Coefficient, K'	MPa	949	1410	-
Cyclic Strain Hardening Exponent, n'		0.166	0.098	-
Fatigue Strength Coefficient, σ'_f	MPa	806	1813	2234
Fatigue Strength Exponent, b	-	-0.083	-0.094	-0.109
Fatigue Ductility Coefficient, ϵ'_f	-	0.351	0.577	-
Fatigue Ductility Exponent, c	-	-0.5	-0.6	-
Hardness, Rockwell C	HRC	6	35	60

DERIVATION OF FATIGUE CONSTANTS FROM SMOOTH SPECIMEN FATIGUE TESTS

The fatigue tests performed to derive the fatigue constants used in this study have stress histories similar to those of Figures 3 and 4. The traditional constant amplitude fully reversed fatigue test has the stress history shown in Figure 3. The test stress history used to determine the effective strain-life curve shown at the left hand side of Figure 4 in which the underloads are applied frequently enough that the crack opening stress is maintained below the minimum stress in the stress cycle and all fatigue cycles are fully effective. These tests were used to determine the crack closure build-up parameter, m , of Equation (2) where the number of cycles between underloads is great enough that the crack opening