Prediction and Simulation of Fatigue Crack Growth Under Conditions of Low Crack Closure

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ABSTRACT

ΔK-decreasing threshold fatigue crack propagation (FCP) data generated under conditions of constant maximum stress intensity (K^c_{max}) are to accurately predict the crack growth behavior of different alloy systems that may experience such low crack closure environments as: the presence of tensile residual stresses, compressive load excursions, and the growth of short cracks. Specifically, K^c_{max} data for a hot rolled steel accurately simulated weld zone FCP rates in a similar steel while K^c_{max} data for 7075-T6 aluminum conservatively bounded FCP rates in a comparable aluminum alloy that was subjected to a cyclic compression precracking procedure. Finally, K^c_{max} data for 6005 aluminum provided an upper bound to short crack FCP rates in this material over the K levels examined. The use of K^c_{max} data in suitable calculations should result in conservative life prediction of engineering components that experience low crack closure conditions.

INTRODUCTION

Conventionally determined (FCP) data generated under ΔK-decreasing conditions at low R-ratios, (ASTM E647) can lead to non-conservative estimates of fatigue lifetimes of engineering structures (1-5). The inability of ΔK-decreasing test procedures to accurately assess a component's service life can be, in large measure, attributed to the generation of excessively large amounts of crack closure at low ΔK levels in the threshold regime (6) of laboratory tests that are not present in actual structures that contain short cracks.

Crack closure occurs due to interference between the mating fracture surfaces behind the advancing crack tip (7). Several closure mechanisms have been proposed for both high K (plasticity induced) and low (roughness induced and oxide wedging) ΔK levels (7-10). Regardless of the operative mechanism, the presence of closure attenuates the effective stress intensity at the crack tip and results in a corresponding decrease in crack growth rates.

This difference between the applied and effective stress intensity is especially significant when laboratory test data is utilized in damage tolerant design of structural components. Many frequently encountered service loading conditions such as: the presence of tensile residual stresses due to welding (1,2,11,12), compressive load excursions caused by variable amplitude loading (13-15), and the growth of physically short cracks (16-21), involve accelerated crack propagation under conditions of greatly diminished closure. As a result, laboratory FCP data generated at low R ratios must be corrected for the effects of crack closure to avoid overly optimistic assessments of fatigue life in actual components (5,9,16).

The determination of ΔK_{eff} values are dependent on accurate measurements of crack closure during the course of the FCP experiment. Unfortunately, such information is often difficult to obtain and subject to scatter, with closure values often dependent on the method by which closure is measured (22). Further, several studies (23,24) have shown that measured closure levels have no bearing on the actual crack growth rates. In fact, Donald (25) has suggested that even when a computerized 'nulling' of the load-displacement signal is performed, closure measurements in the threshold regime are not a reliable tool for predicting intrinsic FCP rates. For example, note the scatter in test results for Astroloy, a nickel base superalloy (26) when FCP data at different R ratios are compared on the basis of ΔK_{eff} levels (fig. 1).

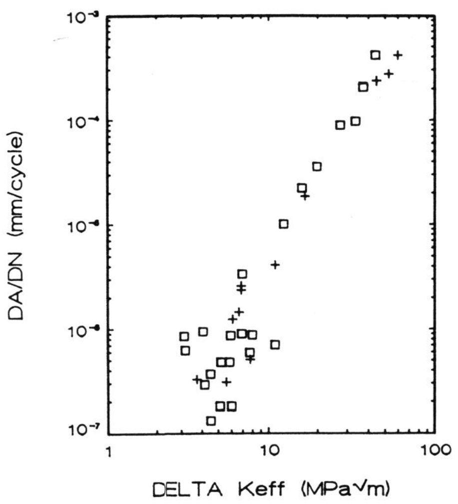

Fig. 1 -ΔK_{eff} FCP data for the fine grained Astroloy (26) nickel alloy. Note the scatter in the data in the threshold region. (+ - R^c = 0.10; □ - R^c = 0.50).

Fortunately, conservative FCP data for use in life prediction can be easily generated in the laboratory by conducting a ΔK-decreasing test procedure in association with a constant maximum stress intensity level (K^c_{max}) (fig. 2) (27-29). By maintaining a constant K_{max}, the mean stress and R-ratio continually increase during the K-decreasing procedure. This results in the generation of long crack FCP data in the absence of crack closure (1,3,20), that should correspond to K_{eff} values but without the experimental scatter due to crack closure effects.

The K^c_{max} threshold test procedure generates data useful in the prediction of the lifetime of engineering components that contain short cracks (1,3,20). Over 85% of available short crack data were accounted for by the long crack K^c_{max} test procedure. This is especially striking in view of the large degree of experimental scatter associated with short crack test results (18).

The objective of this paper is to provide additional verification of the K^c_{max} ΔK-decreasing laboratory test procedure as a useful tool for the damage tolerant design of structural engineering components that may experience low crack closure conditions. Specifically, data will be presented to show that the K^c_{max} test can predict FCP in the presence of short cracks, in weldments and in specimens subjected to compressive loading during the fatigue precracking procedure.

EXPERIMENTAL PROCEDURES

All K-decreasing threshold tests were conducted at ambient under computer control using an Instron Corporation closed loop servo-hydraulic automated test system interfaced with either an Instron-supplied DEC PDP1123 or an IBM XT computer provided by Fracture Technology Associates. The applied stress intensity range was controlled according to the following equation for both constant R ratio (R^c) = 0.10 and K^c_{max} test conditions.

$$\Delta K_i = \Delta K_o * (\exp(C(a_f - a_i))) \quad (1)$$

where:
- ΔK_i = instantaneous stress intensity.
- ΔK_o = current stress intensity.
- a_i = initial crack length.
- a_f = final crack length.
- C = stress intensity factor gradient. $(1/K)*(dK/da)$

Constant R^c = 0.10 fatigue threshold tests were performed for hot rolled 1020 steel, as well as 7075-T6 and 6005 Aluminum alloys to establish the baseline material FCP response. All R^c = 0.10 tests were performed with a stress intensity factor gradient of -0.06 mm^{-1}, with a gradient of -0.20 mm^{-1} being utilized for the K^c_{max} tests. The K^c_{max} tests for these same materials were conducted at K_{max} values of 35.2 MPa $\sqrt{m}$ for the steel, and 10.0 MPa $\sqrt{m}$ and 6.7 MPa $\sqrt{m}$ for the aluminum samples. These K_{max} levels were chosen to ensure that measurable amounts of crack closure would be eliminated prior to the point where crack growth rates entered the threshold regime. A minimum of

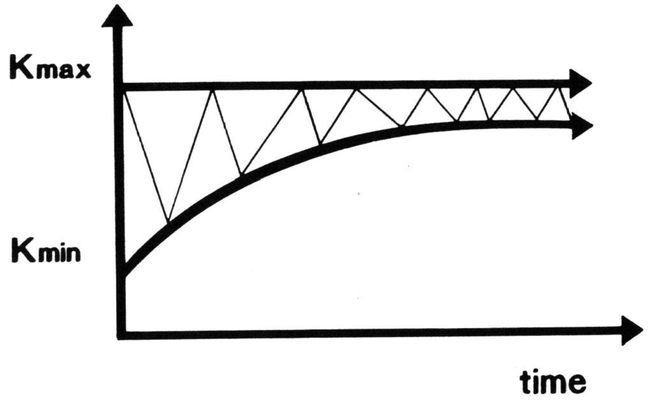

Fig. 2 - Schematic diagram depicting the K^c_{max} threshold test procedure (27-29).

two tests were conducted for each loading condition in order to ensure reproducibility of results.

The long crack fatigue data in this study was determined with the wedge opening load (WOL) sample configuration. Crack length was determined using compliance techniques in conjunction with a crack mouth COD gage. Crack closure levels were monitored throughout the course of the ΔK-decreasing procedure, either through visual observation of a canceled load-displacement trace (generated by signal nulling) or with a computerized closure routine provided with the FTA automated test system (25). Growth rate information (da/dn) was calculated using a modified secant technique.

Short crack FCP tests were conducted on 6005 aluminum using 4 point bend (4PTB) specimens cut from long crack WOL samples tested under both R^c =0.10 and K^c_{max} = 6.7 MPa $\sqrt{m}$ conditions. The surface normal to this through-crack was machined to retain a short crack with a depth no greater than 0.35 mm. The size of the permanent deformation field ahead of the initial short crack tip corresponded to that of the respective long crack K threshold condition; this prior plastic zone was found to have no effect on subsequent short crack growth behavior. Short crack growth rate tests were conducted under constant amplitude loading at R^c = 0.10 until the crack length reached 2.0 mm. Cyclic loading was interrupted periodically to allow for measurement of crack growth with the specimen being removed from the test apparatus and viewed at 100X in an optical microscope.

The R^c = 0.10 and K^c_{max} FCP data for the 1020 steel were compared with data detailing crack growth in as-welded samples of JIS-SB42 steel (11) in order to assess the ability of the K_{max} procedure to predict crack propagation in the presence of

tensile residual stresses. The 7075-T6 K^c_{max} data were compared to data from Nowack and Marrisen (30) who detailed a compressive precracking test procedure (31) designed to eliminate crack closure prior to beginning a standard FCP threshold experiment. Finally, short crack FCP data for 6005 aluminum were compared to the corresponding long crack K_{max} and R^c results.

RESULTS AND DISCUSSION

FCP Behavior of Weldments

Matsuoaka, et al (11) performed R^c = 0.10 ΔK-decreasing threshold tests on base material and on submerged arc welded specimens of JIS-SB42 steel, and noticed much faster crack propagation rates in the welded sample relative to FCP data from the base plate material. The difference in growth rates between the weld metal and baseplate was attributed to the presence of tensile residual stresses in the weldment, which create a high mean stress/low crack closure environment for crack propagation. To confirm this, Matsuoaka conducted a constant maximum load (P^c_{max}) ΔK-decreasing test procedure on the base plate to eliminate crack closure and found these results to be in agreement with the weldment FCP data.

The K_{max} test procedure is a refinement to Matsuoaka's P^c_{max} approach, since the monotonic plastic zone size (r_y) remains constant throughout the K^c_{max} procedure, but continually increases during a P^c_{max} ΔK-decreasing test. When the K_{max} FCP data for a similar steel (hot rolled 1020 steel) are superimposed on the weld zone crack growth data of Matsuoaka for the JIS SB42 steel, the agreement is excellent. Figure 3 shows that the K^c_{max} test is able to accurately predict the FCP response of the weld zone at both high and low ΔK levels.

It should be noted that the 1020 steel used in this test program is comparable in chemical composition, mechanical properties, and low R-ratio FCP response to JIS-SB42 steel (Table 1). Furthermore, previously reported results (3) indicate that the K^c_{max} FCP behavior of JIS-SB42 steel should be similar to 1020 steel. In this regard, it has been shown (3) that 1020 hot rolled steel and 4130 quenched and tempered steel possess similar FCP behavior under K^c_{max} conditions, while their respective R^c = 0.10 results showed an appreciable difference. This correspondence of K^c_{max} data is not surprising, and reflects the ability of the test procedure to measure the material's intrinsic resistance to crack growth.

The excellent agreement between the R^c weld and K^c_{max} test procedure data is most encouraging and reinforces the idea that K^c_{max} data can accurately simulate crack growth behavior in welded specimens, and presumably, in welded structural components. In fact, K^c_{max} FCP data, when used in conjunction with the appropriate R^c curve have been used to accurately predict the SN fatigue lifetimes of large butt welded aluminum beams (3,32).

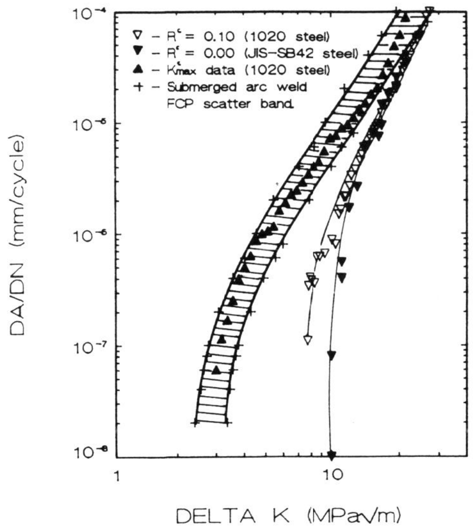

Fig. 3 - Excellent agreement between K^c_{max} data for 1020 steel and the fatigue behavior of a submerged arc welded low carbon steel (11).

Compressive Load Excursions

Since compressive load excursions during service loading may be expected to reduce the level of crack closure due to the crushing of oxide debris and asperities in the crack wake, it follows that closure-free laboratory tests should be able to predict crack growth following an underload. To further investigate this point, ΔK-decreasing FCP data for 7475-T6 aluminum (30) that were generated by precracking in compression to eliminate crack closure (31), were compared with K^c_{max} test results on 7075-T6. As seen in fig. 4, the constant K_{max} data lie at the upper limit of the 7475-T6 scatter band at all stress intensity levels. It may be concluded, therefore, that FCP data generated under compressive cycling conditions during

Table 1 - Comparison of 1020 and JIS-SB42 Steel

(a) Chemical Composition

	C	Mn	Si	Ni	Cr	V
1020	0.18-0.23	0.30-0.60	-	-	-	-
JIS-SB42	0.17	0.81	0.19	0.01	0.02	0.001

(b) Mechanical Properties

	Yield Strength (MPa)	Ultimate Strength (MPa)
1020	210 - 240	390 - 410
JIS-SB42	280	440

precracking and in connection with spectrum loading can be simulated by conducting a simple K^c_{max} threshold test. This follows from the fact that both test procedures involve a closure-free crack wake region. It is also worth noting that the K^c_{max} test results contain much less scatter than that associated with the compression precracking technique.

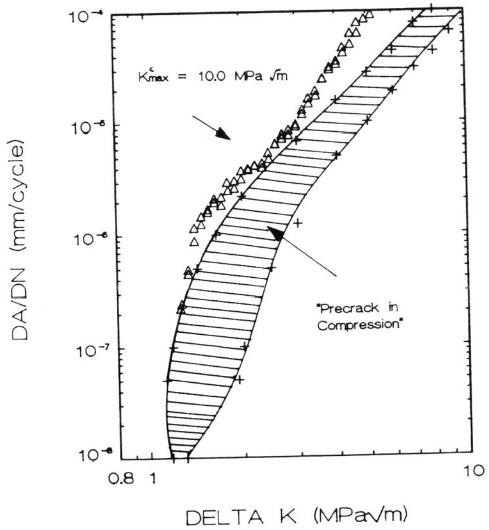

Fig. 4 - Comparison of K^c_{max} FCP data and the "precrack in compression" K-decreasing (30) results.

Short Crack Behavior

Previous studies (1,3,20) have shown that the K^c_{max} threshold test procedure can conservatively predict the FCP behavior of both physically short and microstructurally small cracks in a wide variety of engineering materials. In all cases, up to 85% of the available short crack data from the literature were bounded by the K^c_{max} results, with most of the scatter occurring in the near threshold regime where microstructurally small cracks propagate under conditions of non-similitude. The current work approaches the problem in inverse fashion by first generating the K^c_{max} boundary line, and then conducting 4PTB short crack experiments to determine the validity of this boundary line for the short crack test results. The results of this work are shown in fig. 5, where the $R^c = 0.10$ and K^c_{max} long crack data are plotted together with several sets of short crack growth data. It is clear that over 90% of the short crack growth data is bounded, in a conservative manner, by the K^c_{max} FCP data base.

It is also interesting to note the extreme scatter associated with the short crack test results, with up to a two order of

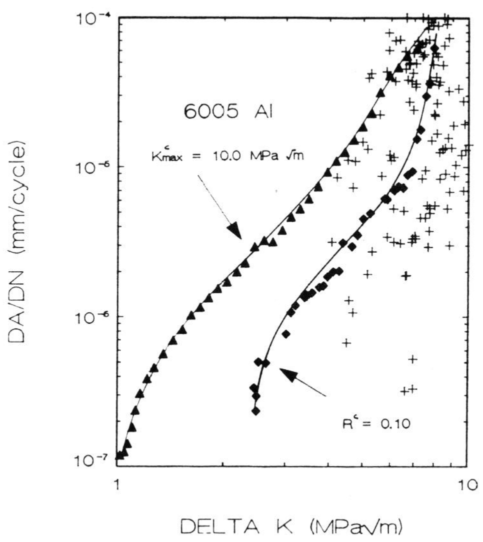

Fig. 5 - Comparison of long crack $R^c = 0.10$ (♦) and $K^c_{max} = 10.0$ MPa $\sqrt{m}$ (▲) FCP data with short crack results (+, $R^c = 0.10$) for 6005 aluminum.

magnitude difference in growth rates seen an any given ΔK level. This amount of experimental inaccuracy is consistent with the nature of short crack growth, and has been widely reported in the literature (18). The inherent inability to accurately and reproducibly characterize short crack growth underscores the utility of the K^c_{max} threshold procedure as an effective tool for determining component life in the presence of short cracks.

CONCLUDING REMARKS

The experimentally simple long crack K^c_{max} test procedure uses standard specimen geometries and is capable of adequately predicting and simulating accelerated FCP in typical structural loading situations associated with short crack growth, tensile residual stresses due to welding, and compressive underloads. Since the K^c_{max} test procedure eliminates the need for crack closure measurements, the associated FCP rates represent a convenient data base by which the intrinsic crack propagation resistance of a material may be determined and with which conservative predictions of component lifetimes may be obtained in an efficient and cost effective manner.

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