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Crack-closure behavior of 2324-T39 aluminum alloy near-threshold conditions for high load ratio and constant K_{max} tests

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ABSTRACT

Fatigue-crack-growth rate tests were conducted on compact specimens made of 2324-T39 aluminum alloy to study the behavior over a wide range in load ratios ($0.1 \leqslant R \leqslant 0.95$) and a constant K_{max} test condition. Previous research had indicated that high R (> 0.7) and constant K_{max} test conditions near threshold were suspected to be crack-closure free and that any differences were attributed to K_{max} effects. During the tests, strain gages were placed near and ahead of the crack tip to measure crack-opening loads from local strain records on all tests, except $R = 0.95$. In addition, a back-face strain gage was used to monitor crack lengths and also to measure crack-opening loads from remote strain records. From local gages, significant amounts of crack closure were measured at the high-R conditions and crack-opening loads were increasing as the threshold condition was approached. Crack-closure-free data, ΔK_{eff} (= U ΔK) against rate, were calculated. These results suggest that the ΔK_{eff} against rate relation may be nearly a unique function over a wide range of R even in the threshold regime, if crack-opening loads were measured from local strain gages and not from remote gages. At low R, all three major shielding mechanisms (plasticity, roughness, and fretting debris) are suspected to cause crack closure. But at high R and K_{max} tests, roughness and fretting debris are suspected to cause crack closure above the minimum load.

1. Introduction

Cracks in high cycle fatigue (HCF) components spend a large portion of their fatigue life near-threshold conditions. In order to characterize the evolution of damage and crack propagation during these conditions, fatigue-crack-growth (FCG) rate data at threshold and near-threshold conditions are essential in predicting service life and in determining the proper inspection intervals. Based on linear elastic fracture mechanics, FCG rate (dc/dN) data are quantified in terms of the stress-intensity factor range, ΔK, at a given load ratio (R = minimum to maximum load ratio) [1]. The relation between ΔK and dc/dN was shown to be nearly linear on a $\log(\Delta K)-\log(dc/dN)$ scale. The relationship becomes nonlinear when the crack approaches fracture [2] or when the FCG rate is very slow [3]. One of the significant mechanisms that influences crack-growth behavior is crack closure, which is partly caused by residual-plastic deformations remaining in the wake of an advancing crack [4,5], roughness of the crack surfaces [6], and debris created along the crack surfaces [7]. The discovery of the crack-closure mechanism and development of the crack-closure concept led to a better understanding of FCG behavior, like the load-ratio (R) effect on crack growth. The crack-closure concept has been used to correlate crack-growth-rate data under constant-amplitude loading over a wide range in rates from threshold to fracture for a wide range in load ratios and load levels [8]. Difficulties have occurred in the threshold and near-threshold regimes using only plasticity-induced crack-closure modeling [9]. The load range where the crack tip is fully open is considered to be the effective range controlling crack growth. To calculate the effective stress-intensity factor range, ΔK_{eff}, the crack-opening load, P_o, was initially determined from load-displacement records using a local displacement gage placed near the crack tip [4,5]. For convenience, however, more recent measurement methods have used either remote crack-mouth opening displacement (CMOD) gages or back-face strain (BFS) gages. These remote measurement methods have indicated that cracks are fully open under high load-ratio conditions. Thus, high load-ratio ($R \geqslant 0.7$) data have been considered to be closure free, even in the threshold regime, and R-ratio effects were attributed to K_{max} effects. In the low-rate regime, at and near-threshold conditions, roughness-induced crack closure (RICC) [6,10] and debris-induced crack closure (DICC) [7,11], have been considered more relevant, but plasticity-induced crack closure (PICC) [8,9] is still relevant under low load-ratio conditions.

The crack-closure concept has not yet been able to correlate data in the threshold regime, either from load-reduction tests at constant R or constant K_{max} tests. Variations in the threshold and near-threshold behavior with load ratio cannot be explained from PICC alone [9], but RICC and DICC mechanisms may be needed to correlate these data. The constant K_{max} test procedure [12] also

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Nomenclature

B	thickness (mm)
c	crack length (mm)
dc/dN	crack-growth rate (m/cycle)
E	modulus of elasticity (MPa)
K_{cp}	compressive stress-intensity factor during pre-cracking (MPa m$^{1/2}$)
K_{Ie}	elastic fracture toughness or maximum stress-intensity factor at failure (MPa m$^{1/2}$)
K_{max}	maximum stress-intensity factor (MPa m$^{1/2}$)
P_{max}	maximum applied load, N
P_{min}	minimum applied load, N
P_o	crack-opening load, N
R	load (P_{min}/P_{max}) ratio
U	crack-opening function, $(1 - P_o/P_{max})/(1 - R)$
W	specimen width (mm)
ΔK	stress-intensity factor range (MPa m$^{1/2}$)
ΔK_c	critical stress-intensity factor range at failure (MPa m$^{1/2}$)
ΔK_{eff}	effective stress-intensity factor range ($U\Delta K$) (MPa m$^{1/2}$)
ΔK_i	initial stress-intensity factor range before load reduction (MPa m$^{1/2}$)
σ_{ys}	yield stress (0.2% offset) (MPa)
σ_u	ultimate tensile strength (MPa)
BFS	back-face strain gage
CMOD	crack-mouth opening displacement
CPCA	compression pre-cracking and constant-amplitude test method
CPLR	compression pre-cracking and load-reduction test method
C(T)	compact specimen
DICC	debris-induced crack closure
FCG	fatigue-crack-growth
HCF	high cycle fatigue
OPn	crack-opening load (P_o/P_{max}) ratio at n% compliance offset
PICC	plasticity-induced crack closure
RICC	roughness-induced crack closure

produces what has been referred to as the "K_{max} effect", in that, lower thresholds are obtained using higher K_{max} values [13,14]. Compared with the constant R test method, constant K_{max} tests gradually decrease P_{max} and increase P_{min} to obtain a reduction in ΔK as the crack grows. One advantage of this test method is that it is commonly considered to produce crack-closure-free data ($R \geqslant 0.7$). But constant K_{max} testing also produces data at variable load ratios (R) and fatigue-crack-growth thresholds at high load ratios (>0.8). For aluminum alloys and high K_{max} values, more dimpling and tunneling on the fatigue surfaces were observed [14], as the threshold was approached. This behavior indicated a change in the damage mechanism from classical fatigue-crack-growth to more of a tensile fracture mode due to the K_{max} levels approaching the elastic fracture toughness. But extensive literature data reviewed by Vasudevan et al [15] on a wide variety of materials do not show the so-called K_{max} effect. These mixed results suggest that something is different in either the test procedure or test specimens that exhibit different behavior in the near-threshold regime.

To generate constant load-ratio data in the threshold and near-threshold regimes, ASTM E-647 [16] proposes the load-reduction test method. But the load-reduction test method has been shown to produce higher thresholds and lower rates in the near-threshold regime than steady-state constant-amplitude data on a wide variety of materials [17–20]. In addition, the load-reduction test method produces fanning of the crack-growth-rate data with the load ratio in the threshold regime for some materials (fanning gives more spread in the ΔK-rate data with the load ratio in the threshold regime than in the mid-rate regime). It has been shown that the test method induces a load-history effect, which may be caused by remote closure [9,17,21]. Thus, the load-reduction test method does not, in general, produce constant-amplitude FCG data, as was originally intended in ASTM E-647. In order to produce steady-state constant-amplitude data, compression–compression pre-cracking methods have been proposed [22–24]. A pre-notched specimen is cycled under compression–compression loading to produce an initial crack, which naturally stops growing (a threshold is reached under compression–compression loading). Then the specimen is subjected to the desired constant-amplitude loading. If the crack has not grown after a million or so cycles, then the load is slightly increased (few percent). This process is repeated until the crack has begun to grow. Then the constant-amplitude loading is held constant and FCG rate data is generated at the desired stress ratio. To achieve steady-state constant-amplitude data, the crack must be grown a small amount (about three compressive plastic-zone sizes) to eliminate the crack-starter notch and tensile residual-stress effects, and to stabilize the crack-closure behavior [18,25]. This method is called compression pre-cracking constant-amplitude (CPCA) loading threshold testing. Another method is to grow the crack at a low ΔK value, after compression pre-cracking, and then use the standard load-reduction test method. Compression pre-cracking allows the initial ΔK value or rate, before load reduction, to be much lower than would be needed or allowed in the ASTM standard load-reduction test method. This method is called the compression pre-cracking load-reduction (CPLR) threshold test method. Both the CPCA and CPLR methods are used herein.

In this paper, FCG tests were conducted on compact specimens made of a 2324-T39 aluminum alloy to study the behavior over a wide range in load ratios ($0.1 \leqslant R \leqslant 0.95$) and a constant K_{max} test condition from threshold to near fracture conditions. During the tests at load ratios of 0.1, 0.7, and 0.9 (except 0.95), strain gages were placed near and ahead of the crack tip to measure crack-opening loads from local load–strain records during crack growth, as shown in Fig. 1. (In retrospect, the failure to install strain gages

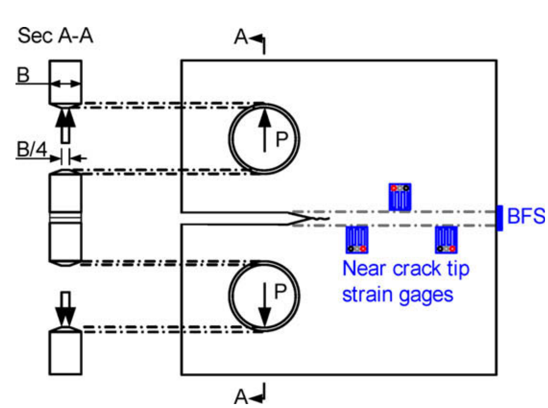

Fig. 1. Compact specimen with local and remote (BFS) strain gages and beveled holes.