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Numerical modeling of fatigue crack propagation based on the Theory of Critical Distances: Effects of overloads and underloads

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A B S T R A C T

A numerical model of fatigue crack propagation based on the Theory of Critical Distances has been developed in a previous paper (Zheng et al., 2013 [1]). The present study aims to investigate the capability of the crack propagation model to predict the effects of overloads and underloads. The plastic energy density at the critical distance ahead of crack tip is affected by the changes in the plasticity-induced crack closure levels and has been used as a measure of the fatigue damage. It is concluded that the predicted crack retardation and acceleration after the overload and underload, respectively, are in satisfactory agreement with the experimental observations.

1. Introduction

In the previous paper [1], a numerical model based on the Theory of Critical Distances has been proposed to predict the fatigue crack propagation in cast aluminum alloys under constant amplitude loading. The condition that the plastic energy density at the critical distance point ahead of crack tip accumulates to a critical value is defined as the criterion for fatigue crack advancing. The crack propagation criterion was established by fitting the simulated crack growth curve to the experimental da/dN vs. ΔK data obtained at R-ratio of 0.1. It has been demonstrated that the crack propagation rates at different R-ratios were correctly predicted using the established crack propagation criterion.

For many engineering components subjected to complex service loadings, crack growth retardation and/or acceleration can occur because of load interaction effects. It is the aim of this paper to investigate the ability of the proposed model to predict the fatigue crack propagation under constant amplitude loading after the application of single overloads (in tension) or underloads (compressive overloads).

It is well known from the experimental observations that tensile overloads may induce crack retardation [2–5]. It has been demonstrated experimentally that crack closure mechanisms play a significant role in the effects of an overload [3,4]. Generally, after a single overload, the crack closure is reduced instantly due to crack tip blunting; after a certain crack extension, the crack closure level reaches a maximum and then decreases asymptotically to the stable level that was present

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Nomenclature

ΔK	stress intensity range
da/dN	crack propagation rate
R	stress ratio
ΔP	applied force range
OL	overload
UL	underload
ΔE	increment of plastic energy density per cycle at one element
OLR	overload ratio
CAL	constant amplitude loading
Δa_{UL}	crack length increment due to the application of a single underload
K_{op}	crack opening stress intensity
a_{UL}	crack length just before underload applied

before the application of the overload. Additionally, measurements have shown that compressive residual stresses are generated ahead of the crack tip after unloading from a single overload [6,7]. The compressive residual stresses are then superimposed to the external applied stresses, reducing the local stress ratio and thus decreasing the crack propagation rate [8]. Some authors have also reported crack closure and crack tip residual stresses levels calculated by finite element method (FEM) that are consistent with experimental observations [9–11]. Based on the FE results, the effective stress intensity range considering the crack closure effect has been used to model the crack propagation rates after a tensile overload is applied [9–11]. A more direct FE approach has been reported by Oliva and Kunes [12]: the variation of crack growth rate after single overload was qualitatively evaluated using the plastic energy dissipation at an element ahead of the crack tip. More recently, Cojocaru and Karlsson [13] established a finite element simulation methodology in which the total plastic energy within the "process zone" ahead of the crack tip (where most of the cyclic damage occurs) was regarded as the controlling criterion for fatigue advancing; the effect of overload on the fatigue crack propagation was also qualitatively predicted.

Compared with the tensile overload effect, the effects due to the application of an underload has been the subject of fewer studies in the literature. Fatigue crack acceleration after a single underload has been reported in the literature by some authors [14–17]. Periodic underloads have also been found to result in a crack growth rate that is higher than the linear summation of the constant amplitude crack growth rates [18–20]. Silva [16] and Yang [21], on the other hand, have reported nearly no effect by the application of an underload. As summarized in [5], the effect of an underload may vary depending on the materials and the loading parameters.

In contrast to the application of an overload, experimental measurements [14–16] indicate that the crack opening stresses are immediately reduced after the application of an underload and then gradually recovered to the stable constant amplitude loading level. The accelerated crack growth rate can then be similarly rationalized through the increase in the effective stress intensity range. Evidence of crushed fracture surface asperities observed by Yu and Ritchie [15] on samples tested with regular underload applications indicates reduced roughness-induced crack closure (RICC). Topper and Yu [20] have also measured compressive local strains at the crack tip after the application of an underload and deduced that the "squeezed" crack tip may cause a decrease in the local compressive residual stresses, resulting in a reduction of the crack closure stresses. Reduced crack closure after an underload has also been predicted by finite element analysis [10].

Despite the extensive usage of the semi-empirical *effective stress intensity range* based on the crack closure concept, few attempts on theoretically modeling the effects of an underload or an overload on the crack propagation rate have actually been performed. In the present investigation, the crack propagation rate after the application of a single overload or underload are predicted using the crack propagation criterion determined from the experimental constant amplitude crack propagation data in the previous paper [1]. The predicted variations of crack propagation rate due to overload/underload are then compared with experimental results. Crack closure behavior is simulated by the finite element modeling and its impact on crack propagation rate is quantitatively captured using the plastic energy dissipation ahead of crack tip as the main damage criterion. Since an underload usually results in crack growth acceleration, the influences of different underload levels and different ΔK levels are investigated through experiments and simulation. The evolution of the crack opening stress intensity and the resultant reversed plastic energy density at the elements ahead of crack tip before and after a single underload are also discussed.

2. Overload and underload experiments

The same E319-T7 cast aluminum alloy and Single Edge Notched (SEN) specimen used in the previous paper [1] were investigated in the present study. The details of specimen preparation, crack length measurement and pre-crack procedure are cited in the previous paper [1]. The experiments were carried out at room temperature on a computer controlled servo-hydraulic MTS testing frame. All tests were conducted under load control at frequencies in the range of 80–170 Hz,