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Effect of low-temperature overload on fatigue crack growth retardation and prediction of post overload fatigue life

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A B S T R A C T

In the present work an attempt has been made to study the simultaneous effect of overload and low temperature on fatigue crack growth behavior. It is known that overload application retards a propagating fatigue crack. It has been observed in this study that application of the overload at low temperature further enhances the magnitude of retardation. Various factors affecting retardation have been analyzed and crack growth behavior is predicted using a modified exponential model. It is observed that the proposed model estimates the crack growth rate and life accurately. The theoretically estimated retardation parameters have been also found to be in good agreement with their experimental values.

1. Introduction

Manufacturing, processing and fabrication introduce some defects and flaws in engineering materials. The application of cyclic and fluctuating loads may initiate fatigue crack and subsequent crack extension from these stress concentration sites. Attainment of a critical length makes the component unreliable and may cause complete failure of the structure. Estimation of crack growth behavior under such loading conditions is essential for stability and safety of structure.

The loading condition, operating temperature and material properties play important role in fatigue initiation and crack growth behavior. It is known that introduction of spike or band overload retards a growing fatigue crack resulting in enhancement of the life of the structure and component. Aircrafts, ships, offshore structures etc. experience such load interactions during their service. The introduction of overload cycle/s has been studied extensively and it is known to retard a growing fatigue crack [2,5,14,26,30,31]. The magnitude of overload induced retardation is a function of overload ratio, position of application of the overload, material properties and the operating temperature.

Wheeler [30] proposed that retardation is achieved due to the compressive residual stress field due to the application of overload cycle/s, and modified the Paris–Erdogan relation [20] by introducing a crack retardation parameter C_p, $\frac{da}{dN} = C_p \cdot (\Delta K)^n$ [31].

Later, Ray et al. [25] introduced the concept of a plastic zone correction factor. It is argued that the presence of a monotonic compressive residual stress field ahead of the crack tip reduces the size of the plane stress cyclic plastic zone, embedded in the monotonic plastic zone.

Though Wheeler's model is successful in predicting the crack growth behavior subjected to single overload cycle, it fails to predict the same under a spectrum loading condition where loading sequence consists of underload and overload spikes. It has long been recognized that the transient crack growth behavior following the application of overload is often controlled by several concurrent mechanistic processes [29]. The plasticity induced crack closure, crack tip blunting/deflection and residual compressive stress field are prominent retardation mechanisms [27]. More recently Pommier [23] has argued that Bauschinger effect may cause reversed plasticity within the region of overload plastic zone which reduces the magnitude of overload retardation.

A few models are available in literature to predict the fatigue life of components subjected to overload cycle [2,5,14,26,30,31]. The earliest of these are based on calculation of the yield zone ahead of the crack tip. Wheeler model [30] and Willenborg model [31], for example, fall in this category. Elber [6], Budiansky and Hutchinson [4] had proposed their models based on crack closure mechanism while Newman proposed a model based on strip

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Nomenclature

a	crack length	mm
a_i	crack length corresponding to the 'ith' step	mm
a_j	crack length corresponding to the 'jth' step	mm
a_{ol}	crack length at overload	mm
a_d	retarded crack length	mm
a_d^P	retarded (predicted) crack length	mm
a_d^E	retarded (experimental) crack length	mm
A', B', C' & D'	material constants in the 'Exponential Model'	
B	plate thickness	mm
C	constant in the Paris equation	
da/dN	crack growth rate	mm/cycle
E	modulus of elasticity	MPa
σ_{ys}	yield strength	MPa
$f(g)$	geometrical factor	
K	stress intensity factor	MPa $\sqrt{m}$
K_C	plane stress fracture toughness	MPa $\sqrt{m}$
K_{IC}	plane strain fracture toughness	MPa $\sqrt{m}$
K_{max}	maximum stress intensity factor	MPa $\sqrt{m}$
K_{max}^B	maximum (base line) stress intensity factor	MPa $\sqrt{m}$
K_{ol}	stress intensity factor at overload	MPa $\sqrt{m}$
ΔK	stress intensity factor range	MPa $\sqrt{m}$
ΔK_{eff}	effective stress intensity factor range	MPa $\sqrt{m}$
l	dimensionless factor in the 'Exponential Model'	
m	specific growth rate	
m_{ij}	specific growth rate corresponding to the interval i–j	
n	constant in the Paris equation	
N	number of cycles or fatigue life	
N_i	number of cycles corresponding to the 'ith' step	
N_j	number of cycles corresponding to the 'jth' step	
N_d	number of delay cycle	
N_d^P	number of delay cycle (predicted)	
N_d^E	number of delay cycles (experimental)	

Table 1
Chemical composition (in wt%).

Al	Cu	Mg	Mn	Fe	Si	Zn	Cr	Others
90.7–94.7	3.8–4.9	1.2–1.8	0.3–0.9	0.5	0.5	0.25	0.1	0.15

Table 2
Mechanical properties.

Tensile strength (σ_{ut}) (MPa)	Yield strength (σ_{ys}) (MPa)	Modulus of elasticity (E) (MPa)	Poisson's ratio (ν)	Plane strain fracture toughness (K_{IC}) (MPa$\sqrt{m}$)	Plane stress fracture toughness (K_C) (MPa$\sqrt{m}$)	Elongation
469	324	73,100	0.33	37.0	95.31	19% over 12.7 mm GL

yield [19]. In addition, there are some retardation models [1,12,24] based on damage accumulation and strain energy release rate. In recent years Mohanty et al. [15–18] have proposed an exponential model based on specific growth rate and loading history.

Working environment and working temperature are among the various factors that influence the fatigue life of a material. Effect of working temperature on fatigue life was first initiated by Zambrow and Fontana [32], who dealt with measurements on magnesium and aluminum alloys and on various stainless steels and observed that the fatigue lives increased with lowering of temperature in contrast to the principle of linear elastic fracture mechanics. It was thought that such increase in fatigue life was due to their increased fracture strength. During the tests conducted by Kwon et al. [11], it was observed that oxidizing environment increased cyclic strain hardening, ultimately increasing fatigue life. Presence of vacuum also causes increased fatigue life of a component than that in air [13]. It was further observed that [7,10,21,28] fatigue life of most FCC materials increased with decrease in temperature whereas, for BCC materials it increased up to DBT after which it became even worse than that at room temperature.

It is well established that temperature affects the mechanical properties of the metallic materials. In the present investigation combined effect of both monotonic overload and low temperature at the point of application of overload has been studied. Aerospace structures are commonly exposed to this situation during their services. Therefore, the present study is carried out for commercially important 2024-T3 Al-alloy. The life estimation and crack growth prediction are important for such structures. An exponential model [16] has been used and attempted for these predictions.

2. Experimental procedure

The present study was conducted on 2024-T3 Al-alloy whose chemical composition and mechanical properties are given in Tables 1 and 2 respectively. Single-edge notched tension (SENT) specimens having a thickness of 6.5 mm were used for conducting the fatigue tests. The specimens were made in the longitudinal transverse (LT) direction. The detail geometry of the specimens is presented in Fig. 1.

The experiments were performed in a servo-hydraulic dynamic testing machine, *Instron*-8502, having a load capacity of 250 kN, interfaced to a computer for machine control and data acquisition. All the fatigue tests were conducted in air and at room temperature except during overloading. The test specimens were fatigue precracked under mode-I loading to an a/w ratio of 0.3 and were subjected to constant load fatigue test (i.e. progressive increase in ΔK with crack extension) maintaining a load ratio, $R = 0.1$. Sinusoidal loads were applied at a frequency of 6 Hz. The crack growth was monitored with the help of a COD gauge mounted on the face of the machined notch. The following equation is used to determine stress intensity factor, K [3].

$$K = f(g) \cdot \frac{F\sqrt{\pi a}}{wB} \tag{1}$$

where,

$$f(g) = 1.12 - 0.231(a/w) + 10.55(a/w)^2 - 21.72(a/w)^3 + 30.39(a/w)^4 \tag{2}$$

The fatigue crack was allowed to grow up to a/w ratio of 0.4 and subsequently subjected to single spike overload cycle at a