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Fatigue crack path manipulation for crack growth rate measurement

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ABSTRACT

It is accepted that fatigue crack paths in metals that display confined slip, such as high strength aluminium alloys, are responsive to loading direction and local microstructural orientation. It is less well recognised that crack paths in these alloys are also responsive to the loading history since certain loading sequences can produce highly directional slip bands ahead of the crack tip. By adjusting the sequence of loads, distinct fracture surface features or progression marks can result, even at very small crack depths. An investigation into the path a fatigue crack selects as it progresses through a material when it is cyclically loaded with particular combinations of constant and variable amplitude sequences has provided insight into the way these cracks grow. This makes it possible to design load sequences that allow very small advances of crack growth to be measured post-test by Quantitative Fractography, at growth rates well below the conventionally recognised threshold of the aluminium alloy examined here.

This paper reports on observations of the dependence of the crack path on the loading history applied to aluminium alloy 7050-T7451 (an important aircraft primary structural material) coupons, which was made possible through the use of novel test loading sequences that produce distinct markings on the crack surface. These markings allow the measurement of crack growth rates at very small crack depths and very low rates of growth in this alloy. The aims of this work were firstly to generate small-crack constant amplitude growth rate data and secondly, to achieve a greater understanding of the mechanisms of fatigue crack growth in this material. A particular focus of this work was the identification of possible sources of crack growth retardation and acceleration in small cracks. The results suggest that for small cracks in this material, the rate of crack growth under variable amplitude loading will tend to be faster than predictions made based on the crack growth rate under constant amplitude loading, due to crack path considerations.

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1. Introduction

The growth of fatigue cracks in metals that display localisation of slip, (or confined slip) develop crack path changes that are dependent not only on the loading direction and the local microstructural orientation of the grains, but also on the loading history. In these materials, certain simple variable amplitude (VA) loading sequences can produce localised plasticity in

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Nomenclature

QF	Quantitative Fractography
K	stress intensity factor
ΔK	the variation of the stress intensity factor at a crack tip due to a single load cycle
ΔK_{th}	threshold stress intensity factor range
K_{max}	maximum stress intensity factor
VA	variable amplitude
CA	constant amplitude
R	smin/smax
σ_{min}	minimum applied far field stress
σ_{max}	maximum applied far field stress
AA	aluminium alloy
T	temper
FEG	field emission gun
SEM	Scanning Electron Microscope
QS	Q-switched
Hz	frequency
MPa	mega pascal
mm	millimeter
da/dN	crack growth rate in meters/cycle
AFM	Atomic Force Microscope

the form of strong confined slip bands ahead of the crack tip, which result from both loading and unloading of each load cycle. The interaction of load cycles and crack tip slip bands strongly influences the crack path. Loading sequences with high R (load ratio = stress minimum/stress maximum) cycles, followed by either significantly different R (low R or $-R$) loading cycles or segments of VA loads, can often produce distinct fracture surface features. These are often referred to as *progression marks*, where a single mark or band is the product of many loads rather than a single load. Further, for single loads the marks produced may not appear as classical striations but as ridges, depressions or fissures depending on previous and subsequent loads. Understanding this behaviour provides a researcher with the valuable ability to use loading changes to steer the crack front [1–3]. This technique has been used here to clearly delineate the crack growth under specific types of loading and thus allow observation of the relationship between crack path features and the loading history, as well as allowing the measurement of the crack growth produced by specific parts of the loading history.

These path changes are investigated here for small cracks produced by simple spectra particular prominent fracture features and their possible causes are briefly discussed. This paper also details how this understanding can be utilised to produce path changes to create progression marks (bands) with constant amplitude (CA) cycles. These are then measured to give crack growth rates/cycle at low-to-very low stress intensity ranges (ΔK[1]). These results and the crack surfaces from which they were drawn are briefly examined for factors that appear to have influenced on local retardation in such bands of crack growth.

The purpose of this work is to improve the understanding of the issues surrounding the progression of fatigue cracks at low crack growth rates through materials that are in common use in aircraft structures. The ultimate aim being to improve the prediction of fatigue crack growth rates for the small crack growth regime, so as to improve the design and maintenance of aircraft structures.

2. Background

The work being reported here was motivated by the desire to improve current fatigue crack growth models so that better predictions of the fatigue lives of critical airframe components can be made. Predicting the fatigue life of aircraft structural metallic components loaded with VA spectra remains difficult, since current methods do not achieve accurate results for crack growth in the small[2] to intermediate size range; a region that often governs the total fatigue life of a component [4–6]. The influence of small crack growth rates on the total fatigue life can be significant for a typical critical component in a combat aircraft since these structures are generally highly stressed. In such cases, it is often found that critical crack depths

[1] It is debatable whether a continuum mechanics-based analysis approach (such as the Linear Elastic Fracture Mechanics, LEFM) parameter K is very appropriate for characterising the progress of fatigue cracking through metals where the growth is well below the grain size of the material and local slip interactions are dominating the crack path. K or ΔK is used here as it allows the results to be put into context with the large volume of results that may be found in the literature. While on a small scale, growth may vary widely due to the local effects of slip, the average growth is less variable and from an average respect the material is acting more like a continuum allowing ΔK to have some meaning in the quest for better predictive capabilities for small cracks it has been shown to work moderately well for these small cracks. Indeed growth rate averaging is the basis for most crack growth rate measurements.

[2] The definition of 'small' in this context may be found in [14].

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