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Fatigue crack acceleration effects during tensile underloads in 7010 and 8090 aluminium alloys

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Abstract

This study investigates the combined action of small amplitude high R ratio cycles and large amplitude low R ratio tensile underloads on fatigue crack growth in aluminium alloys 8090 T852 and 7010 T76351. Compact tension samples were subjected to repeated two level load spectra in which near threshold load cycles at $R = 0.9$ were interrupted with underloads to zero load. K_{op} was measured during underload cycles using a crack mouth gauge. Under these loading conditions crack growth rates are accelerated with respect to the rates calculated from constant amplitude data using linear summation. In 7010, the acceleration was about 30%, in 8090 it ranged from 30% to over 1200%, depending on the number of small cycles between underloads, as well as other loading parameters. Fastest growth rates occurred under loading conditions producing a flat fracture surface and K_{op} levels reduced from the constant amplitude case. It is concluded that there are two mechanisms causing acceleration, both arising from increases in ΔK_{eff} of the underloads in the two level tests. Changes to plasticity based closure produces moderate accelerations of 30% in both alloys; changes to microstructure based closure in 8090 produce additional large accelerations.

Keywords: Aluminium alloys; Fatigue crack growth; Underloads; Crack acceleration; Effective stress intensity

1. Introduction

Despite many engineering components being subjected to load spectra containing tension or compression underloads, in comparison with the number of investigations of the effect of *overloads* there is relatively little research into their influence on fatigue crack growth rates. Examples of components with this type of loading include those in helicopters and gas turbines. A recent review of compressive loading and compressive load excursion research [1] found that it is incorrect to ignore compressive load excursions, as they do contribute to crack growth. It is observed that even tensile underloads cause acceleration of the following constant amplitude loading, reducing the fatigue life [2,3]. Despite this evidence, the contribution to crack growth from underloads, particularly in compression, is usually ignored in design calculations [4]. The effects of periodic underloads during constant amplitude loading and their effects on crack growth rate have to be predicted in order to improve component and structure design, reduce maintenance costs and improve safety.

Topper et al. [5,6] studied crack opening stresses under spectra consisting of original constant amplitude small cycles of a range of R ratios, followed by tension–compression underloads. It was found that the crack opening stress level reduced immediately after the application of the underload and then gradually increased with subsequent constant amplitude cycling. It reached a steady state level after a large number of cycles. The observed crack opening behaviour had a significant acceleration effect when the R ratio was low. At high R ratios (0.8), changes in crack opening stress had no effect on the crack growth rates

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because the crack opening stress was always less than the minimum stress of the loading cycle. Crack growth rate acceleration effects are influenced by the number and the R ratio of the cycles prior to the underload [3,8]. Accelerated crack growth rates exhibit a maximum at a specific number of small cycles. This effect is greatly influenced by loading conditions and material. Fatigue crack closure [8–10], strain hardening ahead of the crack tip due to the underloads and the influence of the mean stress [3] all have been suggested as the underlying mechanisms responsible for accelerated crack growth. Topper and Yu [10] suggested that the compressive underloads caused the squeezed crack tip to have decreased crack closure stress and thus increased the effective stress intensity factor range of the baseline constant amplitude cycles at low R ratio. More enigmatic are the acceleration effects produced by underloads which remain in tension, such as those reported by Fleck [3].

The objective of this study was to investigate the effects on crack growth rates of low R ratio, large amplitude tensile underloads occurring during high R ratio small amplitude cycling. The research was of particular relevance to fatigue of helicopter lift frames and rotor heads. The load spectra of these structures contain large numbers of small amplitude cycles of $R = 0.8$ and 0.9 interspersed with much larger amplitude cycles of R ratio approaching zero. To create the spectrum for study the two components were selected as large cycles of $R = 0$ and small cycles of $R = 0.9$. Two aluminium alloys were selected for study; aluminium 7010, an aluminium–zinc–magnesium alloy, and aluminium 8090 an aluminium–lithium alloy. The effects of the underloads on crack growth rate and on closure behaviour were measured and compared with predictions of crack growth rate calculated using the AFGROW computer model operating without load interaction effects.

2. Materials and experimental techniques

The materials studied were alloys Al 8090 T852 and Al 7010 T73651. Al 8090 is a low density aluminium–lithium alloy alternative to conventional aluminium alloys used in the aerospace industry. The benefits of this alloy are an 8–10% density reduction and 8–10% increase in elastic modulus compared with the 7010-T73651 properties [11]. The specified chemical composition of the alloys is given in Table 1 and the specified mechanical properties in Table 2. It can be seen that 7010 has superior ultimate tensile strength the 0.2% proof strength, has greater elongation, and has 40% better K_{IC} as Table 2 shows. Sections of the alloys were polished, etched and examined metallographically. Sections showing the grain structure in the L–T, planes can be seen in Fig. 1a and b. While the 7010 is relatively equiaxed, the elongated grains of the 8090 can be seen, and were especially marked in the ST–L plane. These observations are consistent with many previous observations on 8090 Al–Li alloys (e.g., [11]).

Constant amplitude fatigue crack growth rate data for the two alloys, at R values of 0.1, 0.4, 0.7 and 0.9, measured on material from the same plate and forgings as used in this work [11,12], are shown in Figs. 2 and 3. It will be seen that both alloys exhibit R ratio effects on growth rate at the threshold and near threshold region, At low R values, particularly at $R = 0.1$ and 0.4, 8090 crack growth rates are markedly more irregular with wider scatter and are slower than growth rates in 7010.

Compact tension (CT) specimens of the two alloys containing fatigue cracks were subjected to underload spectra using a 50 kN capacity Instron 8500 computer controlled fatigue test machine. Tests were performed under load control in laboratory air-(temperature 18–23 °C and humidity ~65%). The samples tested in variable amplitude loading were sourced from the same forgings as those used for constant amplitude tests, and sample dimensions were identical. Samples were 17.5 mm thick with a W dimension of 70 mm. They were machined with the crack plane perpendicular to the L direction, with the crack growing in the T (transverse) direction from a chevron notch of length 14 mm.

Crack lengths were measured using a direct current potential drop (DCPD) technique [13]. Necessary software to control the tests and collect crack growth data was specially written by the authors. The software was also responsible for the transformation of potential data to crack length and for calculation of applied load on the specimen in constant ΔK tests. The noise and drift in the system corresponded to maximum crack length errors of ±0.024 mm noise, and drift ±0.034 mm.

Table 1a
Specified composition of 7010 aluminium

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Zr	Balance
Comp. %wt	0.05	0.07	1.6	0.01	2.3	0.01	5.9	0.11	Al

Table 1b
Specified composition of 8090 aluminium

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Zr	Li	Balance
Comp. %wt	0.04	0.05	1.2	<0.01	0.8	<0.01	0.05	0.03	0.11	2.4	Al