EFFECT OF FREQUENCY ON ENVIRONMENTALLY ASSISTED FATIGUE CRACK GROWTH IN ALUMINIUM ALLOY 7150-T651

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ABSTRACT

The fatigue crack growth behaviour of the high strength aluminium alloy 7150-T651 has been studied in laboratory air and salt solution, as a function of cyclic frequency. Fatigue crack growth rates are seen to be greatly enhanced in salt solution, the enhancement being particularly sensitive to frequency. A simple diffusion model involving hydrogen embrittlement has been applied to the results obtained. This is used to describe the fractographic transition from intergranular to transgranular crack growth observed with increasing stress intensity range, ΔK. The transition itself is considered in terms of the limiting hydrogen distribution necessary for intergranular cracking and enhanced dislocation transport of hydrogen to transgranular sites.

KEYWORDS

Al-Zn-Mg-Cu alloys, corrosion fatigue, cyclic frequency, intergranular/transgranular cracking, hydrogen embrittlement.

INTRODUCTION

High strength aluminium alloys of the 7xxx series have been developed for use in aerospace applications, where their high specific strengths allow considerable savings in weight and cost. Alloy development has concentrated on increasing strength levels whilst maintaining an adequate resistance to stress corrosion cracking, and modern heat treatments allow the attainment of high strength levels and good stress corrosion cracking resistance. However, aircraft are subjected to both monotonic and cyclic loading during service and cracks may propagate under a combination of stress corrosion and corrosion fatigue mechanisms. The relationship between stress corrosion cracking and corrosion fatigue is not straightforward, and corrosion fatigue can occur under conditions where stress corrosion is unfavourable.

Corrosion fatigue in Al-Zn-Mg-Cu alloys in saline environments is dependent on many factors, one of which is the cyclic frequency at which the material is loaded. The response of the fatigue crack growth rates to cyclic frequency can be used to examine the mechanism of corrosion fatigue crack growth. Hydrogen embrittlement is an accepted mechanism for corrosion fatigue in high strength aluminium alloys (Wei et al, 1980; Ricker and Duquette, 1988), where atomic hydrogen generated by reaction at the crack tip is thought to diffuse to the region of high stress triaxiality ahead of the crack and cause brittle crack extension. Although several models exist for corrosion fatigue (Gangloff, 1990), this study considers hydrogen diffusion ahead of the crack as the rate controlling step. The effect of cyclic frequency on a proposed diffusion-controlled mechanism of embrittlement is considered with reference to the fractographic changes from intergranular to transgranular crack growth that occur under certain mechanical conditions.

EXPERIMENTAL

The commercial Al-Zn-Mg-Cu alloy 7150 was supplied by Alcan International Laboratories, Banbury, U.K., in the form of 32mm thick plate in the peak aged T651 temper. The composition is given in table 1. The microstructure of the alloy was examined optically by etching with Keller's reagent (2.5% HCl, 1.5% HNO_3, 1.5% HF) and the grain structure in the fracture plane is shown in Fig.1.

Table 1. Alloy composition in weight %.

Zn	Mg	Cu	Zr	Fe	Si	Ti	Mn	Al
6.22	2.33	2.24	0.12	0.09	0.03	0.03	0.007	balance

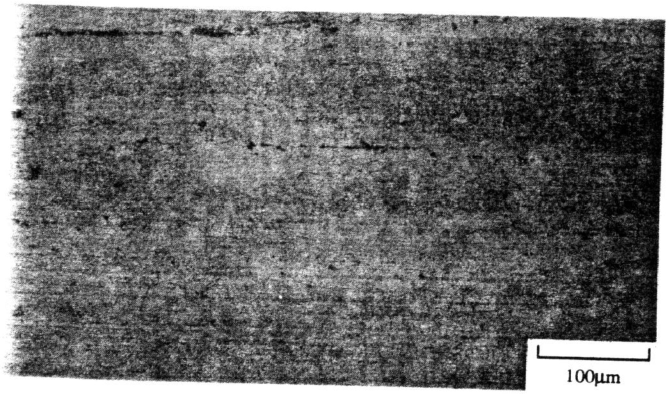


Fig.1. Microstructure in the fracture plane.

Standard compact tension specimens were machined in the S-L orientation such that crack growth occurred parallel to the rolling direction of the plate. Fatigue tests were conducted under constant load range using a 100kN Mayes servohydraulic testing machine with cyclic frequencies between 0.1 and 20Hz at a load ratio ($R=K_{min}/K_{max}$) of 0.3. Crack length was measured using the d.c.p.d. technique and stress intensity factors were determined using the appropriate calibration (Walker and May, 1967). Fatigue crack growth rates were calculated using a seven point secant method.

Tests were conducted at 20°C in both laboratory air and an aqueous salt solution containing 2.5% NaCl, 0.5% Na_2CrO_4, acidified to pH3 with HCl. After fracture the specimens were cleaned in methylated spirits (IMS) and examined in a Camscan S4 scanning electron microscope to determine the mode of fracture.

RESULTS

The fatigue crack growth rates in both air and salt solution over a range of frequencies are shown in Fig.2. Whilst cyclic frequency has little effect on fatigue crack growth rate in air, fatigue crack growth rates in salt solution are highly sensitive to cyclic frequency, with faster growth rates observed at lower frequencies. Furthermore, the fatigue crack growth rates in salt solution are significantly enhanced over those in air, by up to an order of magnitude. The enhancements are relatively constant over the range of ΔK examined, 7 to 16MPa√m, and the growth curves exhibit an approximate Paris exponent of 2.5.

The effect of salt solution on failure mode can be seen in Fig.3. In air, the fatigue failure mode is ductile, with some intermetallic particle cracking at high ΔK. The mode in salt solution is typically more brittle in appearance, with intergranular cracking present at low ΔK, which is replaced at higher ΔK by both crystallographic and flat, striated transgranular crack growth.

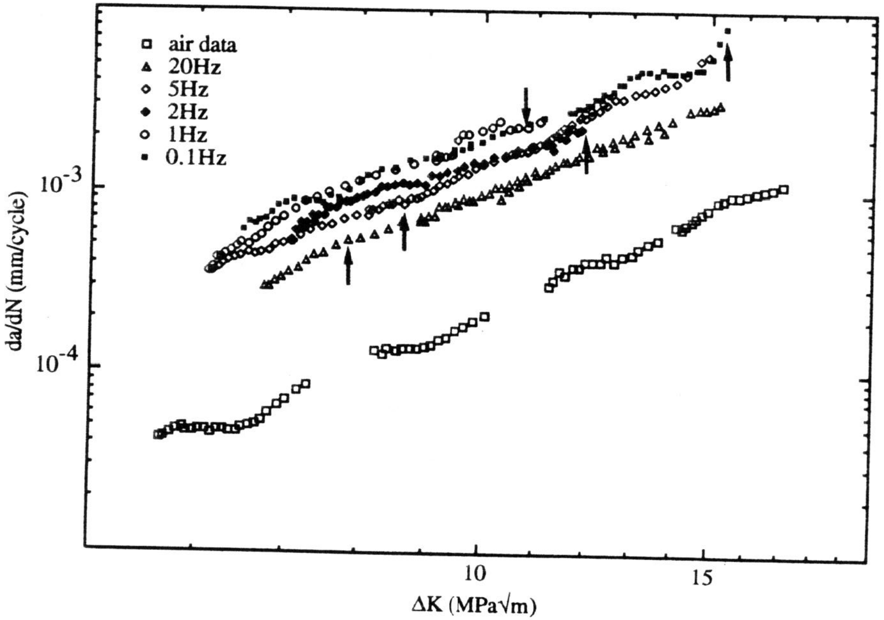
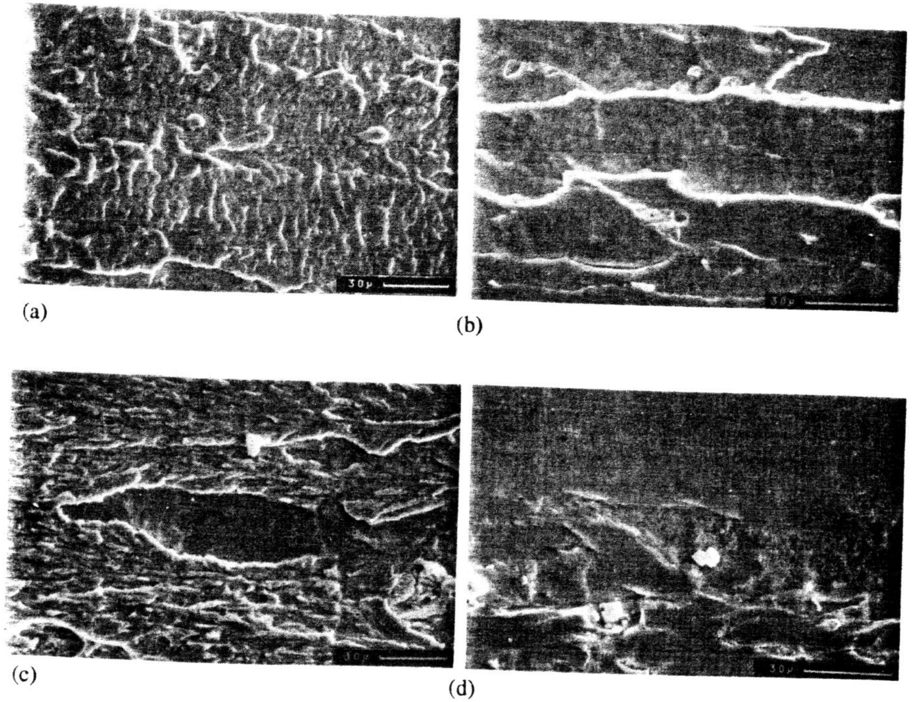


Fig.2. Frequency effects on fatigue crack growth rates in salt solution.

Both intergranular and transgranular growth modes are present at low ΔK, but the extent of intergranular cracking decreases with increasing ΔK and is entirely replaced by transgranular crack growth above a transition ΔK value, indicated for each frequency by arrows in Fig.2. This disappearance of intergranular crack growth with increasing ΔK is found to occur at higher ΔK levels for lower cyclic frequencies. The ΔK level at which intergranular crack growth is no longer seen is taken as the limit of the transition and table 2 shows the values for the range of cyclic frequencies used in the present study.

Table 2. Variation of ΔK for the transition to fully transgranular fatigue with cyclic frequency.

Test frequency (Hz)	ΔK (IG/TG) transition (MPa√m)	da/dN (IG/TG) transition (mm/cycle)
0.1	>15	$>8.2 \times 10^{-3}$
1	10.5	2.23×10^{-3}
2	12	2.21×10^{-3}
5	8.5	8.57×10^{-4}
20	7.9	5.40×10^{-4}



(a) (b) (c) (d)

Fig.3. Characteristic fracture modes: (a) ductile crack growth in air (20Hz, 10MPa√m), (b) intergranular crack growth in salt solution (2Hz, 7MPa√m), (c) crystallographic transgranular crack growth in salt solution (2Hz, 11.5MPa√m), and (d) flat striated transgranular crack growth in salt solution (2Hz, 12MPa√m). Crack growth from right to left.

DISCUSSION

The influence of frequency and stress intensity factor range on the mode of crack growth provides an insight into the mechanism of corrosion fatigue and in particular the factors controlling the mode of crack growth. The transition from intergranular to transgranular crack growth with increasing ΔK has been studied as a function of frequency by Holroyd and Hardie (1983) on 7017-T651, and by Green and Knott (1989) on 7475-T6. Essentially, the transition has been related to the point at which the hydrogen diffusion rate cannot sustain the hydrogen concentration necessary to promote brittle intergranular crack growth, which apparently requires a higher hydrogen concentration than brittle transgranular crack growth (Holroyd and Hardie, 1981; Christodoulou and Flower, 1980). The hydrogen embrittlement process associated with intergranular crack growth involves generation of atomic hydrogen at the crack tip, adsorption into the metal and grain boundary diffusion ahead of the crack tip, embrittling the alloy in the vincinity of the region of hydrogen accumulation. Assuming a constant source of hydrogen is generated and adsorbed at the crack tip during each cycle, the hydrogen concentration profile under steady state conditions will adopt an error function distribution:

$$Cx = Cs\left[1 - erf\left(x/2\sqrt{Dt}\right)\right] \tag{1}$$

where C_x is the hydrogen concentration at a distance x ahead of the crack tip after time t, C_S is the hydrogen concentration at the crack tip, and D is the grain boundary diffusivity of hydrogen within the alloy. Replacing time by N/f, where N is number of cycles and f is the frequency, Eq.1 can be rearranged:

$$x = 2\sqrt{DN/f}\,\mathrm{erf}^{-1}(1 - Cx/Cs) \tag{2}$$

Intergranular crack growth will occur provided that a critical hydrogen concentration C_H can be maintained over a distance x. At the point where intergranular crack growth is no longer sustainable, $x \approx (da/dN)$, so by equating x with the crack extension per cycle (see table 2 for numerical values), and taking logarithms, Eq.2 becomes:

$$\log(da\,/\,dN) = -\frac{1}{2}\log f + \log\left[2\sqrt{\mathrm{D}}\,\mathrm{erf}^{-1}\left(1 - C_H/C_S\right)\right] \tag{3}$$

Hence a plot of $\log(da/dN)_{trans.}$ against log(frequency) should give a straight line with slope -0.5. Using the values in table 2, this plot is shown in Fig.4, to which a straight line with the required slope can be fitted. The expression can be used to determine the grain boundary diffusivity of hydrogen in aluminium, but requires an estimate of the ratio C_H/C_S for intergranular cracking. Using the value of 0.26 quoted by Holroyd and Hardie (1983), Eq.3 gives a grain boundary hydrogen diffusion coefficient of $6\times10^{-13}m^2/s$, which is of the same order of magnitude as other reported values e.g. $3.2\times10^{-13}m^2/s$ in 7017-T651 (Holroyd and Hardie, 1983) and $2\times10^{-13}m^2/s$ in 7075-T6 (Gest and Troiano, 1974). However, this is only a rough estimate as the value of C_H/C_S may itself not be constant but dependent on stress intensity and frequency, in terms of the critical concentration for intergranular cracking and the source concentration at the crack tip, and on the microstructural condition, in terms of the grain boundary chemistry and structure.

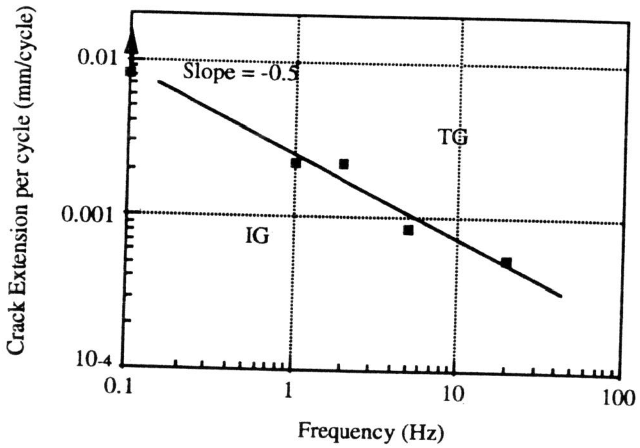


Fig.4. Frequency dependence of intergranular/transgranular transition

The above argument suggests that grain boundary embrittlement will occur provided that hydrogen is present in sufficient concentration. Once the situation is reached where the crack growth increment per cycle becomes equal to the critical hydrogen diffusion distance, a plateau region in the crack growth curve might be expected, where growth becomes time, rather than ΔK, dependent. This would correspond to classical stress corrosion fatigue behaviour. In the present case, fractography shows that brittle transgranular growth modes become more dominant with increasing ΔK. The arrows in figure 2 indicate that there is no evidence of a plateau or change in slope associated with the transition. However the transition from intergranular to transgranular is not sharp, the area fraction of intergranular crack growth decreasing with increasing ΔK, with the values in table 2 corresponding to the disappearance of intergranular growth. Intergranular cracking appears to occur preferentially around the small recrystallised grains. This may occur because these have the highest probability of having boundaries which lie within a few microns of the macroscopic crack plane.

It appears that two competitive mechanisms are operating. Intergranular failure requires a high hydrogen concentration, but the grain boundary acts as both an effective hydrogen trap and a rapid diffusion path. Transgranular embrittlement may occur at lower hydrogen concentrations (Holroyd and Hardie, 1981; Christodoulou and Flower, 1980) but because of the low lattice diffusivity of hydrogen in aluminium cannot occur at these frequencies unless hydrogen is swept into the grain centres and trapped by the dislocation activity in the plastic zone. Sofronis and McMeeking (1989) have analysed the case of hydrogen transport ahead of a blunting crack in steels and suggest that hydrogen embrittlement is linked to the trapping of hydrogen within the region of plastic strain ahead of the crack tip, which would correspond to a distance approximately equal to the maximum crack opening displacement (COD), δ_{max}, Eq.4. Transgranular embrittlement would involve the dislocation transport of hydrogen within this region to transgranular sites (Nguyen et al, 1987; Smith and Duquette, 1986). Thus intergranular failure dominates at low ΔK, where the COD and plastic zone size are small, but transgranular failure becomes more favourable with increasing COD.

$$\delta_{max} = 0.425\frac{(K_{max})^2}{E\sigma_y} \tag{4}$$

Table 3. Values of various parameters in the limit of intergranular crack growth.

f (Hz)	ΔK (MPa√m)	da/dN (μm/cycle)	x_{crit} (μm)	δ_{max} (μm)
0.1	15	8.2	7	5.1
1	10.5	2.23	2.21	2.5
2	12	2.21	1.56	3.2
5	8.5	0.86	0.99	1.6
20	7.9	0.54	0.5	1.4

Table 3 shows the limiting values of ΔK, da/dN and maximum COD (δ_{max}) for intergranular crack growth, and x_{crit} is the distance ahead of the crack over which there is a sufficient hydrogen concentration, C_H, to cause intergranular cracking. The disappearance of intergranular growth is clearly dependent on the extent of grain boundary hydrogen diffusion per cycle, and not on the position of the maximum stress, which would vary with the COD (Sofronis and McMeeking, 1989).

CONCLUSIONS

1. Fatigue crack growth rates in salt solution are significantly higher than those in air. The enhancement is greater at lower cyclic frequencies. These enhancements are accompanied by a change in fracture mode from ductile transgranular to brittle intergranular and transgranular modes.
2. The fracture mode in salt solution is dependent on ΔK and cyclic frequency. Intergranular crack growth is present at low ΔK and low frequency, changing to transgranular crack growth at higher ΔK.
3. The transition to transgranular crack growth is not accompanied by any decrease in fatigue crack growth rate enhancement, indicating that hydrogen embrittlement affects both intergranular and transgranular crack growth.
4. Intergranular crack growth will occur provided that sufficient hydrogen for grain boundary embrittlement can accumulate ahead of the crack during each cycle. When the time per cycle or the grain structure prevent sufficient hydrogen accumulation, the cracking changes to a transgranular crack path.
5. Two competing embrittlement mechanisms appear to be operating. Hydrogen embrittlement of grain boundaries occuring because of grain boundary diffusion and trapping, and hydrogen embrittlement of grain interiors through hydrogen sweep in by dislocation activity in the plastic zone.

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