ENVIRONMENTAL FATIGUE IN GASEOUS ATMOSPHERES IN AN ALUMINIUM ALLOY

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The effect of water vapour pressure and testing frequency on fatigue crack growth in an aluminium alloy is analyzed in this investigation. Fatigue tests were performed in high-purity gaseous atmospheres with different water vapour concentrations and the experimental results were correlated with the morphology of the fracture surfaces examined by S.E.M. The experimental results show that water vapour is the species responsible for the embrittlement. Within a range of pressures and frequencies, the effects of both variables are interchangeable; an increase in pressure has the same effect in the crack velocity than a decrease in frequency. This behaviour confirms the linear dependence of da/dN with the quotient between water vapour pressure and frequency, as theoretically postulated by Wei et al (1-2).

INTRODUCTION

Aluminium alloys are fairly resistant to environmental corrosion in the absence of mechanical tension. However, when subjected to cyclic loads they become sensitive to the testing environment. Some apparently innocuous environments, such as air, are responsible for enhanced crack growth; humid air can increase crack velocity one order of magnitude with respect to high vacuum.

Significant progress has been made in recent years in studying environmental fatigue of aluminium alloys in gaseous environments (1-2). Nevertheless, a detailed mechanistic understanding of the process is lacking. Experimental results point to a hydrogen embrittlement mechanism. In gaseous environments, hydrogen is thought to arise from the reaction of water vapour with the fresh aluminium surfaces created by fatigue in the crack tip region. A model was proposed to explain this phenomenon, based on the idea that crack growth rates depend on the quotient between water vapour pressure and frequency (1-2).

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In the present work the combined effect of water vapour pressure and testing frequency on fatigue crack growth rates in a 7017-T651 aluminium alloy is investigated. Fatigue tests were performed in high-purity gaseous atmospheres with different water vapour concentrations and frequencies and the experimental results were correlated with the fracture surface morphology examined by S.E.M.

MATERIALS AND EXPERIMENTAL PROCEDURE

Medium strength commercial Al-Zn-Mg alloy 7017 (Al 5%Zn 2.4%Mg) in the T651 heat treated condition was employed. The alloy composition and mechanical properties are given in Tables 1 and 2. The microstructure of the 7017-T651 plate consisted of large unrecrystallized "pancake" grains elongated in the rolling direction.

Compact tension specimens (50 mm. width, 5 mm. thickness) were machined from the thirty millimetre alloy plate in the L-T orientation, following the specifications of the ASTM E-647 standard. Fatigue tests were performed in load control at a constant load amplitude with a sinusoidal waveform, at a stress ratio (R) of 0.1. Crack length was measured on one specimen side with a travelling microscope (accuracy of 0.01 mm.). After breaking the sample, the curvature of the crack front was examined and corrected when necessary according to the recommendations of the standard. Crack growth rates were calculated by the secant method.

Tests were performed inside an ultra-high-vacuum chamber specially designed for mechanical testing in precisely controlled gaseous atmospheres, which has been described by Ruiz and Elices (3). Fatigue tests were carried out in high purity gaseous atmospheres with different pressures changing the frequency between 1 and 10 Hz.

Fracture surface morphology was examined by S.E.M and chemical composition of different phases was qualitatively analyzed with E.D.X. Crack advance direction is from left to right in all micrographs.

TABLE 1– Chemical Composition of 7017-T651 Aluminium Alloy (weight %).

Zn	Mg	Fe	Si	Mn	Cr	Cu	Zr	Ti	Al
5.01	2.44	0.23	0.11	0.29	0.17	0.12	0.13	0.05	bal

TABLE 2– Mechanical Properties of 7017-T651 Aluminium Alloy (L-T orientation).

E (Gpa)	$\sigma_{0.2}$ (Mpa)	σ_{UTS}(Mpa)	ε_f (%)	K_{IC} (MPa$\sqrt{m}$)
65.8	415	465	13.7	34.6

RESULTS AND DISCUSSION

In Figure 1 fatigue crack propagation rate, da/dN, is represented as a function of the stress intensity factor amplitude, ΔK, at a fixed frequency of 5 Hz for water vapour (p=5 Pa) and for high vacuum ($p=10^{-5}$ Pa). The data are fitted by means of power law functions ($Y=A\cdot X^m$) and plotted in a log-log scale. For a constant frequency, crack growth rates increase with water vapour pressure (see Figure 1). For $\Delta K \approx 7$ MPa$\sqrt{m}$, where the sharpest differences in da/dN are encountered, crack propagation rate at 5 Pa is twice the value at high vacuum. The fractographic results do indicate a clear difference in the micromechanisms for crack growth in both cases, as can be seen in Figure 2, where the transition in surface morphology which takes place when the environment is changed from high vacuum ($p=10^{-5}$ Pa) to water vapour (p=5 Pa) is shown. In the vacuum side most of the surface is covered with facets perpendicular to the direction of crack growth that have been termed "coarse striations" by Lankford and Davidson (4), typical of the fatigue process in inert environments. However, for water vapour at 5 Pa the fracture surface morphology changes completely. The "coarse striations" are replaced by flat facets with a microscopically brittle appearance which are frequently covered with fine fatigue striations.

According to the model proposed to explain environmental fatigue in gaseous atmospheres (1-2), the parameter which governs crack propagation rates in gaseous environments is the environmental exposure, defined as the quotient between water vapour pressure and frequency. If this statement is correct, the fracture surface morphology must also depend on this parameter.

In order to verify this affirmation experiments were performed where the water vapour pressure was maintained constant meanwhile the frequency was changed during the test. For a water vapour pressure of 10 Pa, changing the frequency between 1 and 10 Hz does not have any effect on the crack propagation rate, as can be seen in Figure 3. The values of the environmental exposure, between 10 Pa·s and 1 Pa·s, lie in the "saturation" region and fatigue crack growth data are very similar to those obtained at 10 Pa and 5 Hz (exposure of 2 Pa·s) by Ruiz (5). When the fracture surfaces are analyzed, no remarkable differences are found between the two testing conditions either. However, for a water vapour pressure of 1 Pa, testing frequency has a great influence on fatigue growth rates. As shown in Figure 4, if the frequency is lowered from 10 Hz to 1 Hz –the environmental exposure changes from 0.1 Pa·s (threshold region) to 1 Pa·s ("saturation" region) (5)–, the crack velocity is increased up to the values corresponding to 5 Pa and 5 Hz (exposure of 1 Pa·s). Furthermore, the effect is totally reversible, since if the frequency is again increased to 10 Hz, the crack propagation rate falls to the previous values. Again the fractographic morphology correlates very well with the macroscopic results of crack growth rate. In Figure 5 the fracture surface appearance in water vapour at a pressure of 1 Pa when the frequency is changed from 10 Hz to 1 Hz can be observed. At 1 Pa and 10 Hz (exposure of 0.1 Pa·s which corresponds to the threshold region) the fracture surface morphology is very similar to that found in vacuum with the characteristic features of the fatigue process in inert environments (see Figure 5a). When the frequency is reduced to 1 Hz in the same environment, the fracture surface appearance changes. In place of the features associated with the fatigue in inert environments, flat facets with a microscopically brittle aspect appear on the fracture surface (see Figure 5b). Often these facets are covered with fine fatigue striations characteristic of the fatigue process in aggressive environments (4). If the frequency is again increased, the features associated with the aggressive environments disappear and the fracture surfaces recover a vacuum-like aspect.

The remarkable correlation between the experimental fatigue crack growth data and the fracture surface appearance, lead to a reliance on the proposed explanation of the embrittlement process. Moreover, the fact that a liquid electrolyte cannot exist in the crack tip –very unlikely at the water vapour pressures employed (5)– leaves hydrogen embrittlement as the only convincing explanation of the environmental fatigue process in this aluminium alloy in gaseous environments.

CONCLUDING REMARKS

Water vapour is the species responsible for the embrittlement process when 7017-T651 aluminium alloy is subjected to cyclic loads in gaseous environments. Preliminary results show that, in agreement with (1-2), environmental fatigue in gaseous atmospheres seems to be controlled by the environmental exposure, defined as the quotient between the pressure and the testing frequency, although additional research is needed to fully corroborate this aspect.

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REFERENCES

(1) Wei, R. P., Pao, P. S., Hart, R. G , Weir, T. W. and Simmons, G. W., Metall. Trans. A, Vol. 11A, 1980, pp. 151-158.

(2) Gao, M., Pao, S. P. and Wei, R. P., Metall. Trans. A, Vol. 19A, 1988, pp. 1739-1750.

(3) Ruiz, J. and Elices, M., Jour. Test. Eval., Vol. 23, 1995, pp. 275-280.

(4) Lankford, J. and Davidson, D. L., Acta Metall., Vol. 31, 1983, pp. 1273-84.

(5) Ruiz, J., Ph. D. Dissert., Universidad Complutense de Madrid, 1993.

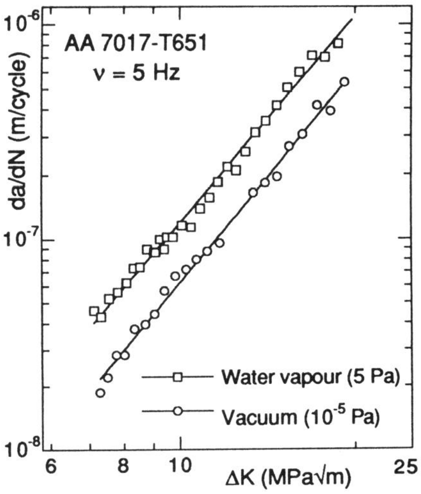

Figure 1 da/dN vs. ΔK in water vapour (5 Pa) and vacuum (p=10-5 Pa) at 5 Hz.

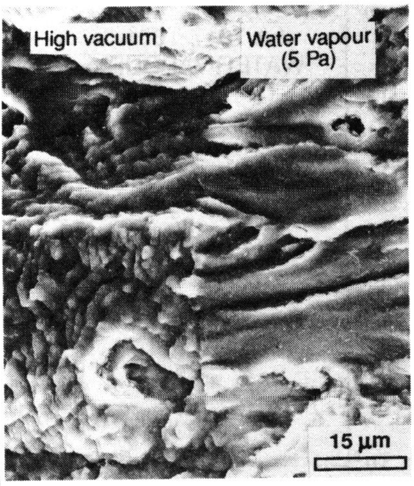

Figure 2 Micrograph of the transition between vacuum and water vapour (p=5 Pa) at 5 Hz (ΔK≈7 MPa√m).

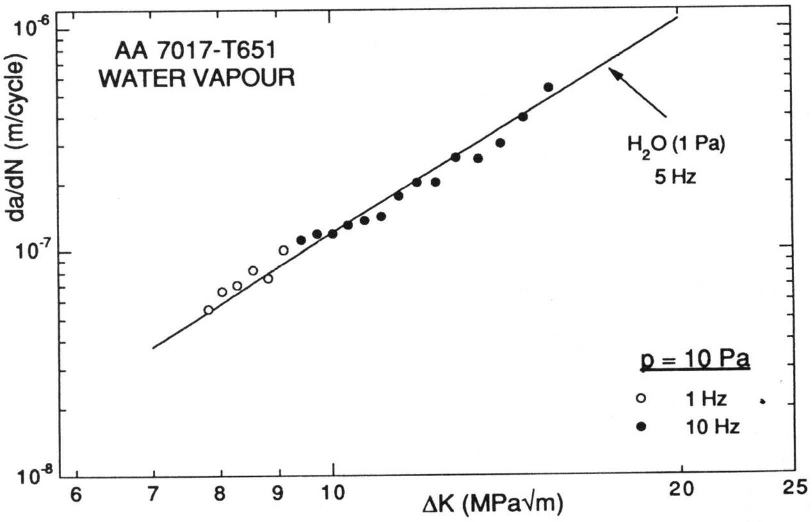

Figure 3 da/dN vs. ΔK for AA7017-T651 tested in water vapour at 10 Pa changing the frequency between 1 and 10 Hz.

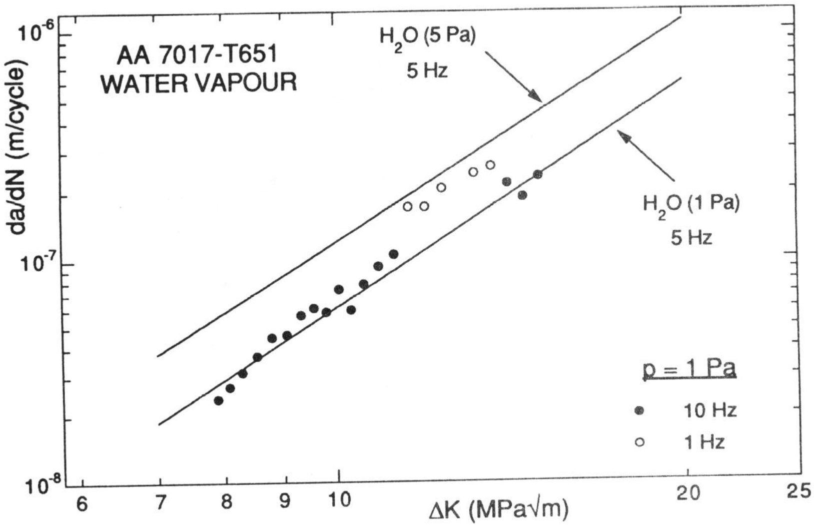

Figure 4 da/dN vs. ΔK for AA7017-T651 tested in water vapour at 1 Pa changing the frequency between 1 and 10 Hz.

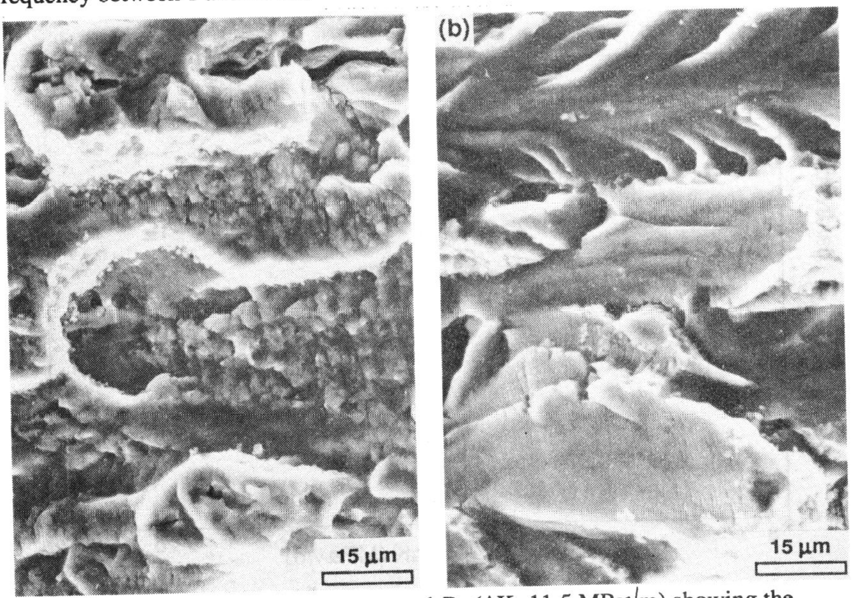

Figure 5 Micrographs in water vapour at 1 Pa (ΔK≈11.5 MPa√m) showing the differences in fracture surface morphology: (a) inert environment appearance (ν=10 Hz), (b) "saturation" water vapour pressure appearance (ν=1 Hz).