VOID COALESCENCE DURING FATIGUE CRACK GROWTH

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The fatigue crack growth characteristics of high strength aluminium alloys are described in terms of behaviour during mechanical testing, and fracture surface appearance. For a wide range of crack growth rates, the crack extends by a combination of ductile striation formation and micro-void coalescence. "Dimples" are observed at stress intensities very much less than the plane strain fracture toughness, and this is explained in terms of the probability of inclusions lying close to the crack tip.

INTRODUCTION

A number of high-strength, wrought, aluminium alloys have been tested, including Al-Cu ("2000 series") and Al-Zn-Mg-Cu ("7000 series") materials with a variety of thermomechanical treatments (1,2).

Mechanical testing has included experiments on both notched, and pre-cracked, specimens, at various stress ratios, and both in laboratory air and in dry, gaseous environments. Cyclic stress-strain data, and crack resistance curves under monotonic loading, have also been recorded. The fracture surfaces were examined using a TEMSCAN electron microscope in both scanning (SEM) and transmission (TEM) modes. This technique was employed to investigate both the crack tip deformation structure, and crystallographic orientation of fatigue cracks. X-ray microanalysis was used to determine the composition of particles on the fracture surface.

EXPERIMENTAL RESULTS

Figure 1 shows fatigue crack growth rate data for one of the alloys tested (2024-T3, naturally aged Al-Cu alloy plate) and includes results for several different test conditions - frequency, thickness, etc. - so that some scatter is evident, but general trends may be observed for a wide range of crack growth rates. Figure 2 shows measured striation spacings from SEM observations. In the present study, the use of a high resolution SEM has enabled direct measurement on the fracture surface of striation spacings as low as 0.04 μm in 7010-T76 Al-Zn-Mg-Cu alloy. A great deal of scatter is apparent, and information from small

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amounts of data, particularly close to the resolution limit, can be misleading. Consequently, Fig. 2 includes some data from other sources (3,4) to indicate broad trends. The following observations are emphasized:

(i) That the macroscopic crack growth rate, da/dN, is higher than that indicated by the striation spacing at high rates, but lower at low rates.
(ii) That da/dN increases with stress ratio, R, for any given value of ΔK, but that there is no systematic variation of striation spacing with R.

SEM and TEM observations give evidence of two morphologically distinguishable modes of crack extension. In a laboratory air environment the first results in a fracture surface which is crystallographic in nature, and which exhibits fatigue striations in many areas. At low ΔK, this mode of growth dominates resulting in a fracture surface composed almost entirely of approximately crystallographic facets. In materials with a strong crystallographic texture, such as thin plate (< 25 mm) and extruded bar, this results in a "rooftop" fracture topography (Fig. 3). The second mode of extension is one of micro-void coalescence resulting in a typical dimpled fracture surface, regions of such fracture often being associated with large inclusions.

The first fracture surface topography dominates for $K_{max} < 10$ MPa$\sqrt{m}$ in all of the alloys studied. With increasing K_{max}, however, regions of dimple fracture become increasingly evident, breaking up the rooftop structure. This transition takes place gradually, until, as K_{max} approaches K_c, the fracture surface is essentially one of dimple fracture (Fig. 4). Note that the proportion of the dimple surface is found to depend more strongly on K_{max} than on ΔK or R.

DISCUSSION

It is proposed that crack growth under fatigue conditions, in high strength aluminium alloys, is the result of three micromechanisms acting together: (i) Ductile tearing; (ii) Plastic blunting of the crack tip; and (iii) Cleavage of environmentally embrittled material.

Ductile tearing is the result of the coalescence of voids which may form by decohesion or fracture of non-deformable particles within the metal. The stress required to initiate such a void depends on the particle size, and on the nature of the particle and its interface with the matrix. The ability of such voids to coalesce with each other, or with an advancing crack front, depends on the strain applied to the intervening ligament. Where a sharp macroscopic crack exists, the strain decreases rapidly ahead of the crack, so that the possibility of crack growth by void coalescence is strongly dependent on the distance between the crack front and the void nucleation site. A simple statistical analysis may be used to estimate the probability of such crack growth (5). If void coalescence were the only mechanism available, the mean distance from the crack front to the next inclusion would be equal to the mean distance between inclusions. A critical stress intensity factor is required to raise the strain over this distance above that required for tensile instability (6). Typical data give a probability of crack growth by tearing greater than 0.95 when

$$K \gtrsim 1.11 E n \sqrt{2\pi \bar{d}} \tag{1}$$

where E is Young's modulus, n is the work hardening exponent and $\bar{d}$ is the mean inclusion spacing (5). The probability falls to 0.05 if K is reduced to $0.9En\sqrt{2\pi\bar{d}}$, and it is this sharp step in the probability of tearing which is thought to define the plane strain fracture toughness, K_{Ic}, or tearing initiation condition (J_o, say?) under monotonic loading.

If there is an alternative mechanism available for crack extension, the crack may grow by that process until its tip is close enough to a void to satisfy the ligament instability condition, and only then extend a short distance by the formation of a dimple. Under these conditions a new probability density function is defined (5). This makes little difference to the value of stress intensity for a tearing probability of 0.95, but for a probability of 0.05 it is found to be reduced to about $0.22En\sqrt{2\pi d}$, i.e. there is a 5% probability of local tearing occuring at stress intensity factors as low as $K_{Ic}/5$. This is an important result, as it introduces the possibility of a significant "tearing" contribution to fatigue crack growth throughout the "Paris Law" régime for many engineering materials.

At these lower stress intensity factors, the major contribution to crack growth is clearly from a mechanism resulting in crystallographic fracture, and, in many cases, fatigue striations. Observations have been made using combined SEM and TEM (7) enabling the fracture surface topography to be related to dislocation substructure. In a laboratory air environment this reveals a structure of uniformly spaced bands of high and low dislocation density, spatially related to the fatigue striations. It is concluded that the initial part of the crack extension in each cycle occurs with little or no plastic deformation, but that this is followed by additional crack growth and blunting of the crack associated with greatly increased plasticity. TEM observations made on specimens tested at different values of R have shown that the form of dislocation substructure produced is related to ΔK, and is independent of R (8). In a dry oxygen or argon test environment, low dislocation density regions, crystallographic fracture and clearly defined striations are all absent, giving strong evidence for a cleavage involvement in the initial stages of crack extension. It is believed that hydrogen, liberated by a water/metal interaction at the crack tip, is transported ahead of the crack by dislocations, causing local embrittlement.

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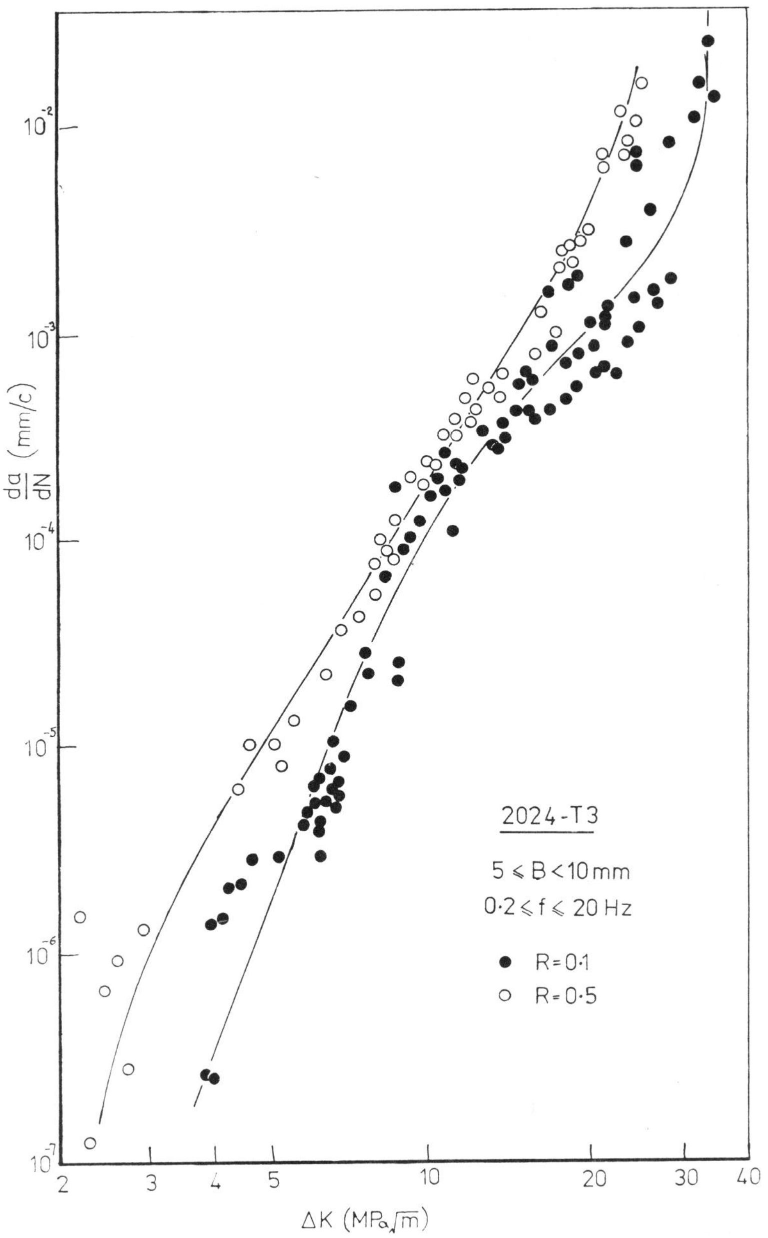

Fig. 1. Fatigue crack growth in a typical high strength aluminium alloy

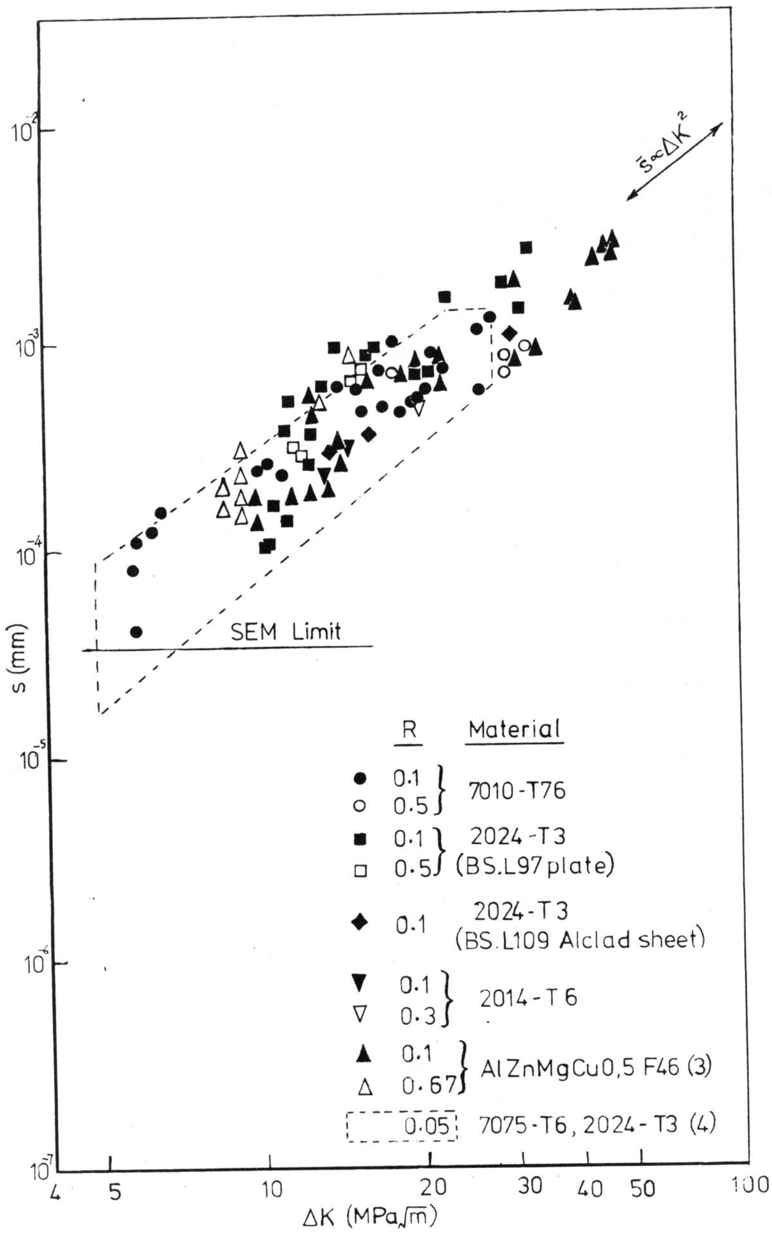

Fig. 2 Striation spacing in high strength, wrought, aluminium alloys

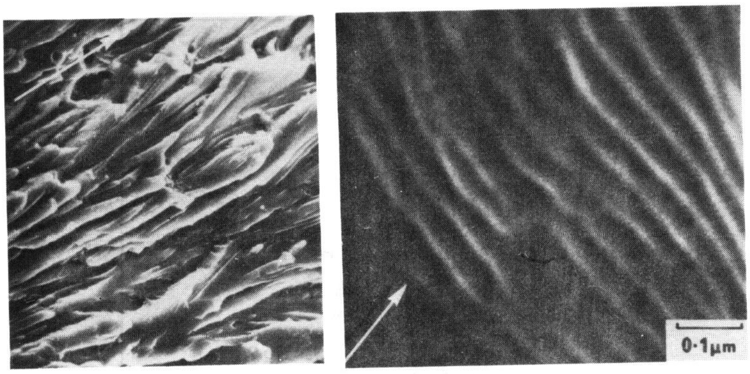

Fig.3 $\Delta K \simeq 6MPa\sqrt{m}$

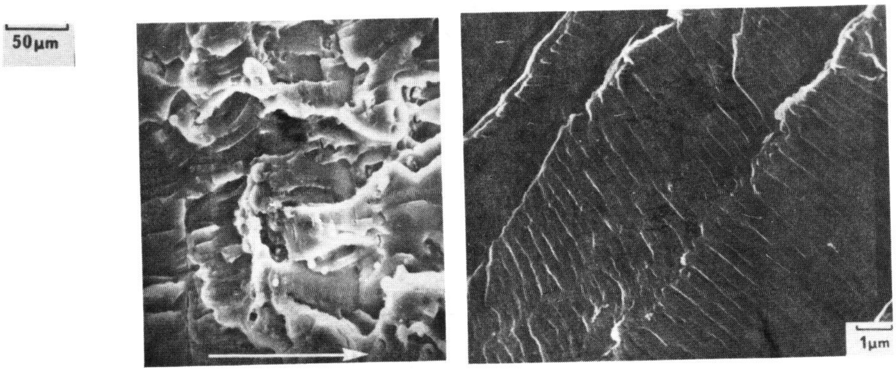

Fig. 4a) $\Delta K \simeq 16MPa\sqrt{m}$

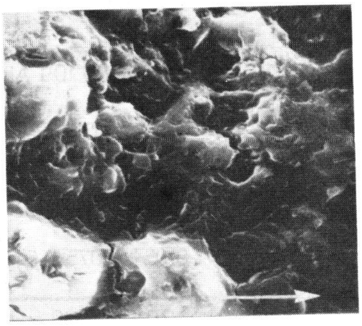

Fig. 4b) $\Delta K \simeq 25MPa\sqrt{m}$

Figs.3-4 Change in fracture surface topography with increasing ΔK.