FATIGUE CRACK INITIATION AND PROPAGATION IN Al-Zn-Mg SINGLE CRYSTALS AND ITS DEPENDENCE ON THE AGEING TREATMENT

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High cycle fatigue crack initiation and propagation has been studied in precipitation hardened Al-Zn-Mg single cristals . In peak-aged and underaged specimens tested in a dry nitrogen atmosphere ,crack initiation and propagation was in stage I. In overaged specimens tested in a dry nitrogen atmosphere and in laboratory air, crack propagation was in stage II. The crack propagation rate in stage II was much lower than in stage I. The larger particles in the overaged condition suppress PSB formation and crack propagation changes from stage I to stage II. In the latter case the influence of remaining moisture in dry nitrogen gave a large effect at low crack propagation rates.

INTRODUCTION

The fatigue properties of precipitation-hardened alloys show a strong dependence on their microstructure and therewith on the heat treatment of the material. In addition, environmental conditions also play an important role. In order to get a better insight and understanding of the influence of the microstructure and the environment on the initiation and propagation of fatigue cracks in a high strength aluminium alloy a series of experiments were undertaken on single crystal specimens of an Al-Zn-Mg alloy. The results will be discussed in terms of the interaction of the proceeding crack with the surrounding atmosphere.

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EXPERIMENTAL DETAILS

Single crystals were prepared by a strain-annealing technique from a high purity hardenable Al-4.5wt.%Zn-1.25wt.%Mg alloy provided by VAW, Bonn. The rod-shaped cylindrical crystals were machined by spark erosion into flat samples having a rectangular cross section of 1.5 x 5.5 mm^2. The specimen axis was oriented for single slip with its broad surface parallel to the Burgers vector of the primary slip system. This slip plane made an angle close to 45° with the longitudinal direction of the specimen.

All samples were homogenized for 30 min at 480°C,water quenched and electrolytically polished. Notches of about 500 μm depth were spark machined into the narrow side of the specimens, and they were aged at 135°C for different times (see Table 1). Underaged (UA1 and UA2), peak-aged (PA) and overaged (OA) specimens were fatigued either in laboratory air or in dry nitrogen atmosphere. The moisture content was measured by a capacitance method throughout the experiment. All specimens were fatigued electrodynamically using a constant stress amplitude (R = -1) at a frequency of 100 Hz.

TABLE 1 - Ageing Treatments for the Al-Zn-Mg Specimens at 135°C and Their Critical Resolved Shear Stress.

Type of Specimen	t_a(h)	CRSS(MPa)
UA 1	1	60
UA 2	10	95
PA	10^2	140
OA	10^3	105

Crack initiation and propagation were measured quantitatively with a travelling microscope at 200 x magnification in the X- and Y-directions. The detection limit for this method is better than 5 μm. To account for different orientations of the cracks, the stress intensity factor ΔK for crystallographic cracks was calculated using mode I and mode II stress intensities to obtain an average ΔK:

$$\Delta K^2 = (\Delta K_I)^2 + (\Delta K_{II})^2 \quad (1)$$

Both quantities were calculated for the crack geometry of the samples according to Knott (1) without correcting for the finite size of the specimens. For non-crystallographic cracks propagating perpendicularly to the long specimen direction, only mode I is dominant and a correction function for fixed grips described by

$$f(a/w) = 5/\sqrt{[20 - 13(a/w) - 7(a/w)^2]} \qquad (2)$$

was used (2). For better comparison with the results on stage I cracks uncorrected data are also represented.

EXPERIMENTAL RESULTS

Crack Initiation and Fatigue Lifetime

The fatigue lifetime N_f can be separated into two parts (3), the number of cycles to crack initiation, N_i, and the number of cycles for crack propagation up to failure, $\Delta N = N_f - N_i$. Crack initiation is defined here as a detectable crack length of about 50 µm measured from the notch of the specimen to the crack tip. Fig.1 shows the stress dependence of both N_i and N_f in dry nitrogen atmosphere for all four different ageing treatments. In the double logarithmic presentation the N_i data can be fitted by a single straight line for all ageing treatments with the exception of UA1. In this case the N_i values are lower than the others by a factor of 5.

The straight lines for the fatigue lifetime N_f in Fig.1 are probably the same for UA2 and PA specimens but differ by a factor of 10 to the corresponding line for the OA specimens which is shifted to longer lifetimes. In contrast, some preliminary experiments on UA1 specimens show a drastic decrease in N_f in comparison to the UA2 and PA specimens.

Crack Propagation in Dry N_2 Atmosphere

Figure 2 shows the cyclic crack propagation rate da/dN in dry nitrogen atmosphere for all ageing treatments as a function of the stress intensity factor ΔK at 100 Hz. For better comparison with the stage I results the uncorrected data of stage II crack propagation have been plotted as a dashed line on this figure. In the intermediate ΔK region no difference in the crack propagation rate for the underaged and the peakaged specimens was found. The crack propagates crystalographically as a stage I crack and a dependence

$$da/dN = \text{const}\ (\Delta K)^m \qquad (3)$$

with m = 4 was found. The points shown in Fig.2 for the OA specimens are taken from three independent experiments at stress amplitudes between 66 and 70 MPa.

For the OA specimens the crack propagates non-crystallographically (stage II) and a linear dependence between log (da/dN) and log ΔK was only found for da/dN > 10^{-9} m/cycle with m = 8, while crack propagation rates smaller than 10^{-9} m/cycle show a plateau range, i.e., no dependence on ΔK up to nearly the threshold value. Comparing the crack propagation rate for OA specimens with those for the UA1, UA2 and PA specimens, a large difference is observed. For the stress intensity factor ΔK = 10 MPa$\sqrt{m}$, the OA specimens show a crack propagation rate which is nearly 10^3 times smaller than the rates for the other specimens.

Crack Propagation in Laboratory Air

The surprising results for OA specimens with the large plateau region suggest an important influence of the environment. Therefore, experiments in laboratory air were mainly undertaken with OA specimens. Experiments on UA and PA specimens are in progress. Fig. 3 compares the results of crack propagation in laboratory air and in dry nitrogen. The partial pressure of the water vapor was 1750 Pa compared to 35 Pa for the dry nitrogen environment. Both curves have the same threshold value ΔK = 3.8 MPa$\sqrt{m}$ but otherwise differ considerably. The curve for the laboratory environment experiment shows a much faster propagation rate with only a small plateau range. The latter has been observed at small crack lengths where an influence of the notch on the propagation rate cannot be excluded. For larger ΔK values both curves approach each other and may meet at a crack propagation rate of 5 µm/cycle for ΔK = 37 MPa$\sqrt{m}$. In this range the slopes m of the curves are 4 and 8, respectively.

DISCUSSION

Fatigue experiments on age hardened Al-Zn-Mg single crystals in dry nitrogen (4) and on Ni-alloys in oxygen (5) have shown that under these conditions crack propagation is predominantly in stage I. In Al-Zn-Mg specimens fatigued under strain control the rapid nucleation of cracks in the PSBs at the surface is caused by strong localized shear (6).

For notched specimens fatigued under stress control (σ<0.4 CRSS) one or more PSBs are nucleated at the notch root and propagate in the dislocation band, which spreads parallel to the primary slip plane. Thereafter, a crack forms and finally follows one of these PSBs (7). Crack nucleation, induced by PSBs, has been observed for underaged and peak-aged specimens fatigued in dry nitrogen atmosphere.

The mechanical behaviour of both precipitation states is characterized by the presence of shearable η'particles which make the alloy susceptible to localiced deformation by softening effects due to particle shearing. Under cyclic loading conditions TEM experiments have shown that the heavy to and fro shearing induced by localized slip cuts the small particles into pieces (7). This leads to further softening and strain localization inside the PSBs.

For overaged specimens, TEM examinations have shown that besides the η' particles stable η precipitates were formed which are incoherent with the matrix (8). This favours the bypassing mechanism and supresses the tendency to localized straining inside the PSBs which decrease in length. Therefore, the crack changes from stage I to stage II.

The Influence of Environment

For the PA condition the influence of the environment on crack propagation has been discussed elsewhere (9). It has been shown that the moisture embrittles the PSBs in front of the stage I crack tip which increases the stress concentration. As a result a change in crack propagation rates can occur (4). If the dry condition is reestablished the crack propagation rate returns to the original value.

In this paper the influence of moisture on the stage II crack propagation of the OA specimens will be discussed. The present results in Fig.3 clearly show that at very low crack propagation rates (da/dN < 10^{-10} m/cycle) the threshold value for propagation in both environments is ΔK = 3.8 MPa$\sqrt{m}$. This suggests that in this case the micromechanisms of crack propagation should be the same. The dry nitrogen still contains a small amount of water vapor which may, at these small propagation rates, be sufficient to cause the same mechanism as in laboratory air. At high ΔK values, both curves seem to approach each other and may meet again at a rate larger than 10^{-6} m/cycle. In that case it is suggested that for these high speeds moisture no longer has an important influence. In between these both limiting rates the difference in moisture of the two atmospheres plays an important role and should explain the different behavior of the two specimens. Comparable results as those shown in Fig.3 have been observed also by Petit (10) who performed experiments on commercial aluminium alloys in vacuum, laboratory air and nitrogen. Recent experiments on a polycrystalline Al-Mg-Sc alloy also show similar results (11).

According to Wei et al. (12) three processes are necessary in order for moisture to affect crack propagation. These are:

(i) transportation of the water vapor to the crack region,

(ii) adsorption of the vapor on the newly created crack surface and its dissociation into oxygen and hydrogen,

(iii) diffusion of the hydrogen into the plastic zone in front of the crack tip.

The latter step is thought to be so fast that it is only rate controlling at very large propagation rates such as where the curves in Fig.3 meet each other.

Studies of the effect of gaseous environment on fatigue properties of aluminium alloys have shown that in many cases a critical partial pressure of water vapor p_{crit} is needed to enhance fatigue crack propagation (12,13). In this model, enhancement of cyclic crack propagation is assumed to result from the reaction of water vapor with freshly produced fatigue crack surfaces. Bradshaw and Wheeler (13) suggested that the degree of the enhancement of cyclic crack propagation in aluminium alloys by water vapor is determined by the exposure (vapor pressure x time) during each half-load cycle. If only water vapor is present Achter (14) found the following relationship between the critical propagation rate and the vapor pressure:

$$da/dN\ /_{crit} = 3.7 \cdot 10^{-7}\ p_{crit}/f \qquad (m/cycle) \qquad (4)$$

If the crack propagation rate is smaller than this critical value, the crack surface is totally covered by water vapor and the crack growth is enhanced by embrittlement. Calculations of the critical crack propagation rate assuming f=100 Hz and p_{crit} = 35 Pa leads to propagation rate values of nearly 10^{-7} m/cycle. The experimental results have shown, however, that the critical crack propagation value represented by the beginning of the plateau range has been measured as 10^{-9} m/cycle. The discrepancy between these data may be explained by two different mechanisms which reduce the adsorption rate of water vapor. At first the presence of nitrogen reduces the effect of water vapor. As an example, it has been found recently that the critical partial pressure of water needed for crack acceleration has to be increased from 100 to 300 Pa if the environment is changed from vacuum to nitrogen (15). Secondly, according to Wei et al. (16), the transportation of the vapor to the crack tip may be the rate controlling process which can reduce the effective vapor pressure at the tip by two orders of magnitude compared to the pressure in the environment.

CONCLUSIONS

Fatigue experiments in dry nitrogen atmosphere performed on age hardened Al-Zn-Mg single crystals show stage I crack initiation and propagation for underaged and peak-aged specimens. For overaged specimens stage II crack propagation is observed in dry nitrogen as well as in laboratory air. In both atmospheres the stage II crack propagation rate is very low compared to that of stage I cracks, due to the presence of non-shearable large particles in overaged specimens which hinder the formation of PSBs, leading to stage II crack propagation. The present results show that at very low crack propagation rates the threshold value for stage II crack propagation is the same in both dry and wet environments. This suggests that, at low crack propagation rates, embrittlement by water vapor must take place even in a nominally dry atmosphere which still contains small amount of water.

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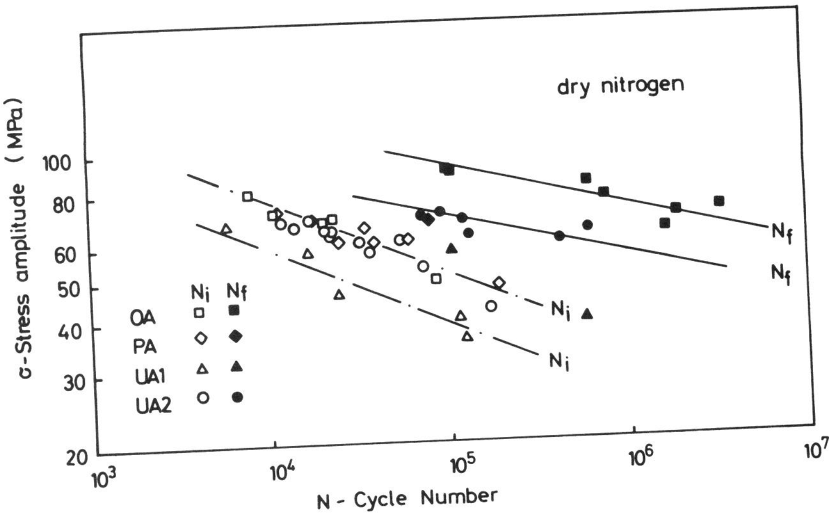

Figure 1 Number of cycles to crack initiation N_i and fatigue lifetime N_f versus σ

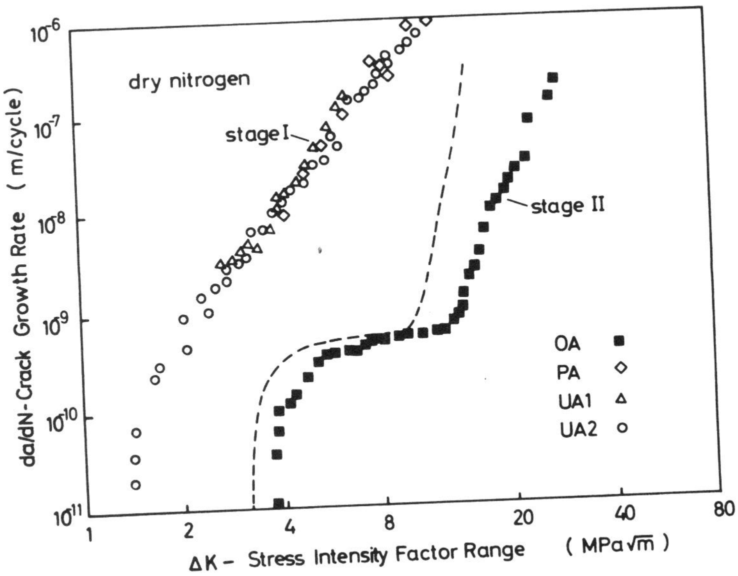

Figure 2 Crack propagation rate versus ΔK for specimens fatigued in dry nitrogen

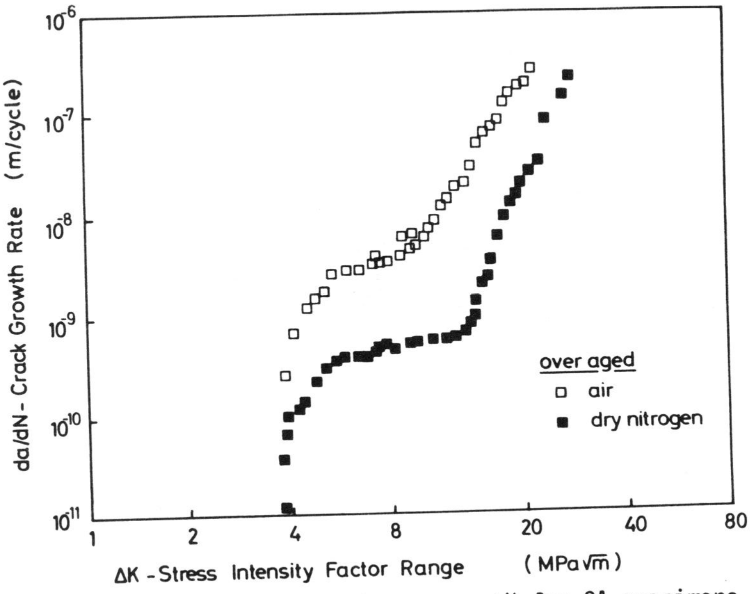

Figure 3 Crack propagation rate versus ΔK for OA specimens fatigued in laboratory air and in dry nitrogen