INFLUENCE OF GRAIN SIZE ON THE FRACTURE OF ALUMINUM ALLOYS

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INTRODUCTION

It has been proven for many alloys especially for the lower yield point of steels, that the grain size has an influence on the tensile yield stress. However, an influence of grain size on other mechanical properties such as ductility, fatigue properties, and crack propagation is still uncertain. Recently it was shown for a variety of Ti-alloys [1, 2] and for an austenitic steel [3] that the tensile ductility increased with decreasing grain size. For some microstructures an effect of grain size on crack propagation was reported [3, 4] but the results are still contradictory [5]. For Al-alloys it was shown that the true fracture stress increased with decreasing grain size [6].

The purpose of the present work was to investigate the influence of grain size on the fracture behaviour of high strength Al-alloys for two different deformation and fracture mechanisms [7] which are shown schematically in Figure 1. Mechanism A is observed for alloys containing particles which can be sheared by the moving dislocations leading to the formation of intense slip bands. These slip bands are able to produce offsets in grain boundaries (crack nucleation sites) and a transcrysalline fracture occurs along these intense slip bands. If upon aging precipitate-free zones (PFZ) develop along grain boundaries preferred plastic deformation occurs within these weak zones and cracks are nucleated presumably at grain boundary triple points. The fracture is then intercrysalline (mechanism B).

EXPERIMENTAL PROCEDURE

The investigation was performed on a high purity Al-5.7 wt.% Zn-2.5% Mg-1.5% Cu alloy, supplied by the Schweizerische Aluminium AG, Neuhausen, Switzerland. Due to the high purity almost no inclusions were present in this alloy. Homogenization of the alloy at 738K for 1 hour followed by quenching in ice-water produced a grain size of 220 μm. A small grain size of 50 μm was obtained by the following additional steps: Aging at 653K for 5 hours to precipitate coarse n-particles, immediately after ice-water quenching from 653K cold rolling to a deformation degree of φ = 0.69, recrystallization at 653K and homogenization at 713K both for 10 minutes and both followed by ice-water quenching. All specimens were kept at room temperature for about 2 days before aging them at 373K and 443K for various times.

Tensile tests were carried out on round specimens with a diameter of 6 mm and a gage length of 25 mm. The strain rate was 6.7 x 10⁻⁴ s⁻¹.

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The fracture surface was investigated by scanning electron microscopy. Fatigue life tests were performed on round electrolytically polished specimens (diameter 4 mm) under push-pull loading at constant stress amplitudes by light microscopy.

RESULTS

The dependence of tensile properties on aging time at 373K is shown in Figure 2 for specimens with the large grain size of 220 μm. The yield stress 0.2 increased continuously whereas the true fracture strain $\varepsilon_f$ declined.

The true fracture stress 0.2 reached a slight maximum after 100 h aging time. The observed fracture mechanisms are indicated in Figure 2. In the as-quenched condition and after short aging times, a marked "DIMPLE" is present in the fracture surface. With increasing aging time, intense slip bands are observed in the region marked "SLIP BANDS" (Figure 2). After an aging time of 1000 h at 373K, narrow precipitate-free zones are formed along grain boundaries which deform preferentially and fracture mechanism 8 (Figure 1) is observed by GB (PE2) in Figure 2.

The dependence of tensile properties on aging time at 433K is shown in Figure 3. At high aging temperatures the yield stress passes through a maximum indicated by a pronounced minimum occurring at a low value of 0.08. The ductility $\varepsilon_f$ increases again a slight maximum in this case at short aging times.

A comparison of the tensile properties for the two grain sizes is given in Table 2. Again no difference in yield stress 0.2 was found. Both the true fracture stress 0.2 and the true fracture strain $\varepsilon_f$ increased with decreasing grain size for this deformation and fracture mechanism 8. The increase of $\varepsilon_f$ from 0.10 to 0.42 is remarkable. The corresponding fracture surfaces revealed that for the large grain size the typical ductile fracture along grain boundaries covered the whole surface (Figure 7a) whereas for the small grain size the portions showed a sharp crystalline fracture mode increased (Figure 7b). The dimple spacings were similar to those observed for specimens aged 24 h at 373K (see Figure 6b). On the flat grain surfaces small dimples become visible at higher magnifications resulting from interfacial decohesion of the incoherent γ-particles present at the grain boundaries.

Fracture Mechanism A

For the investigation of the influence of grain size on mechanical properties for the two deformation and fracture mechanisms A and B two and 20 h at 373K for mechanism 8.

Fracture Mechanism A

The tensile properties for the two grain sizes investigated are shown in Table 1. It can be seen that the yield stress 0.2 did not vary within 24 h at 373K. With decreasing grain size the true fracture stress $\varepsilon_f$ increased and also the true fracture strain $\varepsilon_f$ from 0.55 to 0.68. The corresponding fracture surfaces are shown in Figure 4.
DISCUSSION

For the high strength aluminum alloy investigated the results of tensile tests are in agreement with the view that an inhomogeneous distribution of plastic deformation induced by weak zones (sheared particles for mechanism A and PF2 for mechanism B) has a deleterious effect on the macroscopic mechanical properties [7]. This deleterious effect increases with explaining the observed dependence of tensile ductility on aging time (Figures 2 and 3). A pronounced effect of grain size was found on crack nucleation for the two different deformation and fracture mechanisms A and B [Figure 1]. In both cases a reduction in slip length [1, 2] (grain diameter for mechanism A and grain boundary length for mechanism B) leads to reduced stress concentrations delaying crack nucleation and improving therefore the tensile fracture properties (Tables 1 and 2) and the fatigue properties (Figures 5 and 8). For tensile experiments this delay in crack nucleation for mechanisms A and B leads to the appearance of a different crack nucleation mechanism for specimens with the small grain size of 30 μm. Voids are nucleated within the matrix at intersecting slip bands [5] which coalesce and form dimples visible on the fracture surfaces (Figures 4b and 7b).

One difference in crack nucleation mechanism for the deformation modes A and B can be clearly seen by comparing the appearance of fatigue surface cracks (Figures 6 and 9). For the case of preferred plastic deformation within PF2 (mode B) cracks appeared perpendicular and parallel (push-pull loading) to the loading direction (Figure 9a). This proves that the cracks nucleated at grain boundary triple points induced by pronounced plastic deformation within PF2 along boundaries lying at an angle of about 45° to the loading direction [2].

Although a pronounced influence of grain size on crack nucleation was found there seems to be no or only a small effect on crack growth. The fact that no difference in yield stress $\sigma_{y}$, between specimens with grain sizes of 220 μm and 30 μm was found in this work as well as for some Ti-alloys [1, 2] raises the question which microstructural conditions are responsible for the dependence of yield stress on grain size observed for many other alloys.

ACKNOWLEDGEMENT

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REFERENCES

1. GYSLER, A., TERLINDE, G. and LÜTJERING, G., Proc. 3rd Int. Conf. on Titanium, Moscow, 1976.
Figure 1  Deformation and fracture mechanisms investigated (schematically).
A: Slip band fracture  B: Grain boundary fracture (PFZ)

Figure 2  Tensile properties ($\sigma_{0.2}$, $\sigma_F$, $\epsilon_F$) versus aging time at 373K

Figure 3  Tensile properties ($\sigma_{0.2}$, $\sigma_F$, $\epsilon_F$) versus aging time at 433K.
Figure 4  A: 24 h 100°C
Tensile Fracture Surface (SEM)
(a) Grain size 220 µm, ε_p = 0.35.
(b) Grain size 30 µm, ε_p = 0.65.

Figure 5  A: 24 h 373K
S-N curves for two grain sizes (220 µm and 30 µm)

Figure 6  A: 24 h 373K
Fatigue crack nucleation, σ = ± 200 MPa, (LM)
(a) Grain size 220 µm, N_f = 300 000 cycles
(b) Grain size 30 µm, N_f = 1 350 000 cycles

Figure 7  B: 20 h 433K
Tensile fracture surface (SEM)
(a) Grain size 220 µm, ε_p = 0.10
(b) Grain size 30 µm, ε_p = 0.42
Figure 8  B: 20 h 433K
S-N curves for two grain sizes (220 µm and 30 µm)

Figure 9  B: 20 h 433K
Fatigue crack nucleation, σ = ± 200 MPa, (DM)
(a) Grain size 220 µm, Np = 200 000 cycles
(b) Grain size 30 µm, Np = 700 000 cycles