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Low cycle fatigue properties of Al-Li-Cu-Mg-Zr alloy processed by equal-channel angular pressing

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Equal-channel angular pressing (ECAP) is a process in which the ingot is subjected to a very severe plastic strain without any change in the cross-sectional dimensions. Numerous reports have confirmed that ECAP is a promising technique for achieving grain refinement in bulk materials. It was demonstrated [1] that the as-processed materials have unusual physical and mechanical properties. ECAP has been applied to different materials, but studies on fatigue properties of ECAP materials were still scarce [2, 3]. In this paper, low cycle fatigue properties of Al-Li-Cu-Mg-Zr alloy processed by ECAP were investigated.

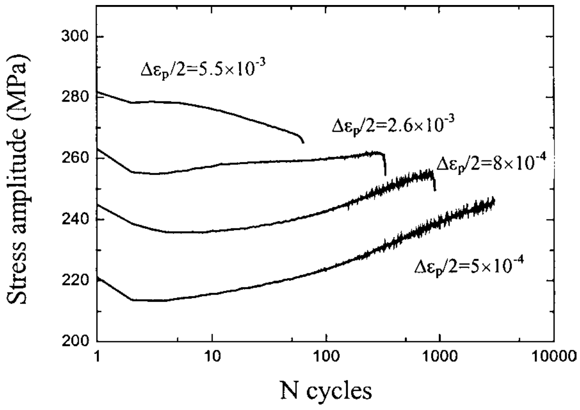

Figure 2 Cyclic stress response of ECAP Al-Li-Cu-Mg-Zr alloy.

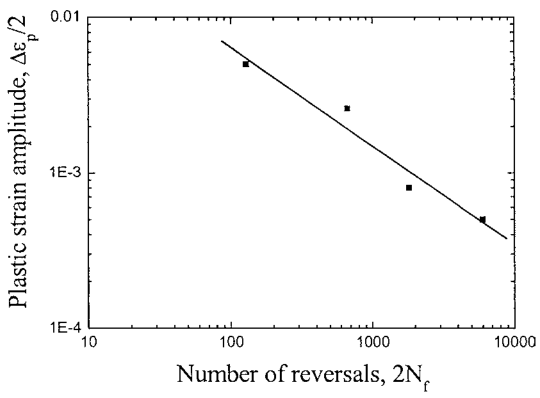

Figure 3 Coffin-Manson plot of ECAP Al-Li-Cu-Mg-Zr alloy.

Al-Li-Cu-Mg-Zr alloy used in this investigation has a composition (in wt%) of 2.55Li, 1.55Cu, 1.13Mg, 0.13Zr, 0.12Fe, 0.11Si, balance of Al. The samples were pressed through the 90° intersecting channel and were rotated through 180° about working axis between 4 subsequent passes. The pressing was conducted at a temperature of 270 °C with the sample held in the die for 20 min to establish thermal equilibrium prior to pressing. The alloy underwent solution treatment at 530 °C for half an hour before pressing. Fatigue specimens of 3 × 4 mm in cross-section were cut by spark cutting and then mechanically polished to obtain a mirror-like surface. Fully reversed tension-compression fatigue tests were performed on MTS testing machine under total strain amplitude control, using a clip-on axial extensometer. A strain amplitude range of 10^{-3}–10^{-2} was chosen. The plastic strain amplitudes $\Delta\varepsilon_p/2$ at half fatigue life $N_f/2$ were used to construct the Coffin-Manson plot. Since the tensile testing at room temperature indicated that the effect of strain rate in the range of 10^{-3}–10^{-1} s^{-1} on the flow stress of ECAP aluminum alloys was not significant [4], all fatigue tests were conducted at 1 Hz. Thin foils for transmission electron microscopy (TEM) were first sliced perpendicular to the pressing axis, then mechanically thinned down to about 60 μm thick and finally polished by a standard twin-jet polishing method using an electrolyte of 25%

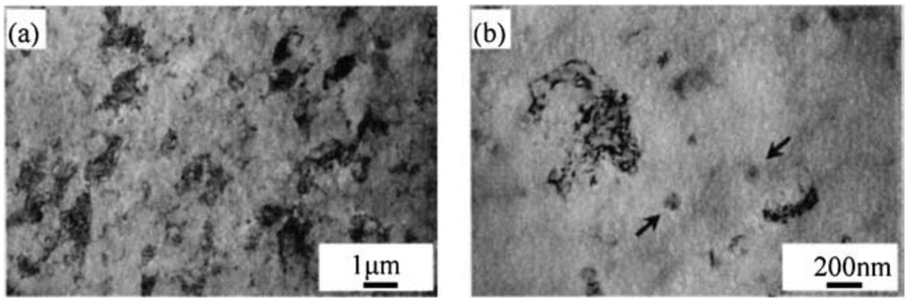

Figure 1 TEM micrographs showing the microstructure of ECAP Al-Li-Cu-Mg-Zr alloy: (a) grains and subgrains and (b) δ' precipitates (as arrows show).

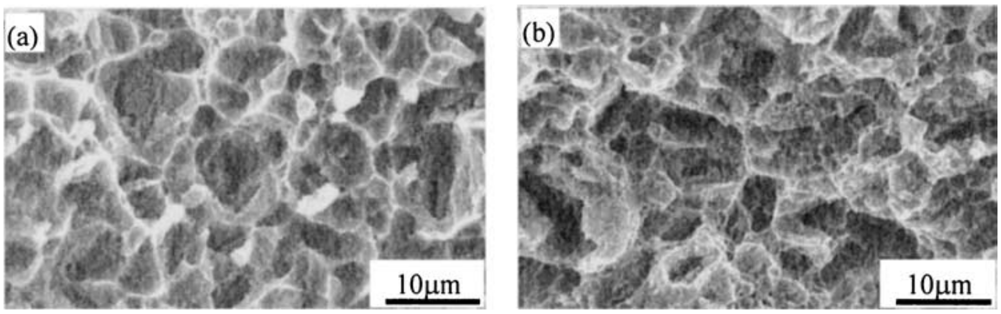

Figure 4 SEM micrographs of fatigue fracture surface of ECAP Al-Li-Cu-Mg-Zr alloy: (a) $\Delta\varepsilon_p/2 = 5.5 \times 10^{-3}$ and (b) $\Delta\varepsilon_p/2 = 8 \times 10^{-4}$.

nitric acid and 75% methanol at −20 °C. TEM observation was carried out using a JEM 2000FX II microscope operated at 200 kV. Fractographic observations were performed using scanning electron microscopy (SEM).

Extensive investigations on microstructural evolution in pure Al during ECAP were reported [5]. It has been shown that a rather equi-axial grain structure can be obtained in Al alloys through repetitive pressing. Fig. 1a is a typical TEM micrograph showing the microstructure of ECAP sample. It mainly consists of near equi-axial grains smaller than 1 μm. Some of the grain boundaries in Fig. 1a are not very clear because the angles are low. The dislocation density in the grains is not very high. However, for most ECAP metals and cold worked metals, the dislocation density is very high [3]. It might be reasonable to suppose that dynamic recovery process happened during ECAP process. A few and sparse δ' precipitates can be seen in TEM micrograph of ECAP samples (Fig. 1b).

Fig. 2 is the cyclic stress response of the ECAP Al-Li-Cu-Mg-Zr alloy. The cyclic stress response shows unusual characteristics different from most of other ECAP materials. Most of ECAP materials cyclically soften as cold worked materials [3], while the ECAP samples in this experiment show a complicated cyclic stress response. At strain amplitudes of $\Delta\varepsilon_p/2 = 5 \times 10^{-4}$–$2.6 \times 10^{-3}$, samples soften rapidly at first few cycles, and then harden continuously till failure. The initial cyclic softening may be associated with the reduction of dislocation density because of annihilation of dislocations during cyclic straining. The subsequent cyclic hardening is supposed to be resulted from a combination of increase in dislocation-precipitates interaction and dislocation-dislocation interaction. Furukawa *et al.* [6] have suggested that in Al-Li alloys when the precipitates have diameters less than 50 nm, dislocations shear the precipitates; when the precipitates have diameters more than 50 nm, dislocations by-pass the precipitates. The precipitates in the ECAP sample have diameters about 100 nm (Fig. 1b), dislocations by-pass the precipitates and form Orowan loops around precipitates and the complex dislocation interaction around precipitates leads to cyclic hardening. At higher strain amplitude of $\Delta\varepsilon_p/2 = 5.5 \times 10^{-3}$, ECAP samples soften continuously until failure. One possible reason of continuous softening is that some low angle and unstable grain boundaries were penetrated by dislocations at higher strain amplitudes. Valiev *et al.* [7] indicated that grain boundaries in ECAP material are highly non-equilibrium with high energy. When the applied plastic strain is high, grain boundaries will easily be penetrated by dislocations and softening occurs. Further investigation is required to attest the mechanisms of softening and hardening.

Peak-aged Al-Li-Cu-Mg-Zr alloy exhibit non-ideal plastic strain-fatigue life response with a slope change in the Coffin-Manson plot [8]. One of the explanations for the slope change in the Coffin-Manson plot is based on a change from planar to homogeneous deformation as a function of plastic strain amplitude, which is related to the shearable δ' precipitates [9]. However, as shown in Fig. 3, ECAP Al-Li-Cu-Mg-Zr samples in the present study show a straight line in the Coffin-Manson plot. As mentioned above, the δ' precipitates in ECAP samples are large and sparse, the dislocations by-pass the precipitates. So whether the strain amplitude is higher or lower, the deformation is homogeneous. As a result, the slope change in Coffin-Manson plot does not appear and the ECAP samples show a straight line. Fig. 4 shows the fatigue fracture surface of ECAP samples of $\Delta\varepsilon_p/2 = 5.5 \times 10^{-3}$ and $\Delta\varepsilon_p/2 = 8 \times 10^{-4}$. There are no significant differences in fracture mode between them and intergranular fracture is the main fracture mode, which confirm that the dislocations by-pass the precipitates and the deformation is homogeneous under either higher or lower plastic strain amplitudes.

In summary, Al-Li-Cu-Mg-Zr alloy processed by ECAP has some unusual fatigue properties.

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