EFFECT OF EQUAL CHANNEL ANGULAR PRESSING ON MECHANICAL PROPERTIES OF AZ91 ALLOY

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Specimens of a fine-grained AZ91 alloy were prepared using equal channel angular pressing (ECAP). The deformation behaviour of the AZ91 alloy after multi-angular pressing was estimated at testing temperatures between 20 and 300 °C. The values of the yield stress and the maximum stress of ECAP specimens deformed at room temperature are higher than those of initial specimens. The elongation to fracture (ductility) increases with increasing test temperature and with number of extrusion.

K e y w o r d s: equal channel angular pressing, mechanical properties, magnesium alloy

VLIV ÚHLOVÉHO PROTLAČOVÁNÍ SE STEJNÝM PRŮŘEZEM NA MECHANICKÉ VLASTNOSTI SLITINY AZ91

Vzorky slitiny AZ91 s velmi jemným zrnem byly připravené úhlovým protlačováním se stejným průřezem. Vzorky byly deformovány v intervalu teplot 20 až 300 °C. Hodnoty meze kluzu a maximálního napětí pro protlačované vzorky deformované při pokojové teplotě jsou vyšší než pro neprotlačované vzorky. Deformace do lomu roste s rostoucí deformační teplotou a s počtem protlačování.

1. Introduction

Magnesium alloys, the lightest structural metallic materials, have been widely used as structural components in industry due to their excellent strength-weight ratio. However, the disadvantages of these materials are the poor workability

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because of their h.c.p. structure and a low corrosion resistance. They exhibit limited ductility at ambient temperatures and an increase in ductility with increasing temperature. On the other hand, the mechanical properties of magnesium alloys decrease rapidly with increasing temperature [1]. Very recently, the model describing this behaviour has been proposed [2]. An improvement of the mechanical properties of magnesium alloys may be achieved by reinforcement of the alloys with ceramic fibres or particles. An increase in the strength of Mg composites depends not only on the matrix but also on temperature as shown by Trojanová et al. [3, 4] and Drozd [5].

It is well known that materials with a small grain size have excellent mechanical properties. A reduction of the mean grain size is expected to increase the yield stress (and the ultimate tensile strength) of a material at room temperature and to promote superplastic properties at higher strain rates and/or lower temperatures than those conventionally used in superplastic forming. A very fine structure can be produced by equal channel angular pressing (ECAP) technique (in the literature the process is also termed equal channel angular extrusion) [6].

In ECAP process, the material in rod form is pressed through a die containing two channels which are equal in cross-section. The channels intersect at an angle Φ. The material is subjected to deformation that approximates to simple shear. The cross sectional dimension of the sample remains the same after the pressing. Therefore, the sample may be pressed repetitively. Thus, very high strains may be achieved (without any change in the cross-sectional dimensions). Straining leads to a substantial grain refinement. Microstructures with ultra-fine grain sizes in the submicrometer or nanometer range may be introduced. The microstructures developed after ECAP depend on many factors: rotation of the specimens between consecutive passes; a number of the passes through the die (an increase of a total strain); the nature of the slip systems [7]. The pressing temperature may also influence the microstructure. One of the most important parameter of ECAP process is the number of extrusions. The most important refinement of the microstructure takes place during the first pressing (pass). With increasing number of passes the elongation to failure is increasing but, on the other hand, the yield stress or the maximum stress shows only a small change.

Magnesium alloys, because of their low density, have many potential applications. They exhibit high specific strength, but low ductility at room temperature. Among the most commercial magnesium alloys used, AZ91 alloys dominates. Yamashita et al. [8] have reported that pure Mg and Mg-0.9 wt.% Al showed significant improvement in both strength and ductility at room temperature even after one pass through the ECAP die. The yield stress of these materials was related to the square root of the grain size (the Hall-Petch relationship) and the elongation to failure was between 15 and 20 %. The average grain size was about 17 μm after pressing at 200 °C. Mabuchi et al. [9–12] have reported that AZ91 alloy processed by ECAP, with a very small grain size of about 1 μm, showed a large elongation to failure of 661 % at 200 ℃ and at strain rate of 6×10^{-5} s^{-1}.

The aim of the present paper is to study the effect of ECAP on the mechanical properties of an AZ91 magnesium alloy in the temperature range from room temperature to 300 ℃ and at strain rate of 5×10^{-4} s^{-1}.

2. Experimental procedures

The AZ91 magnesium alloy used in this investigation contained 9 wt.% Al, 1 wt.% Zn and 0.2 wt.% Mn. The alloy was solution-treated for 18 h at 413 ℃. The heat-treated samples with dimensions of $10 \times 10 \times 60$ mm^3 were pressed using an ECAP die. An internal angle between the vertical and horizontal channels was 90°. The rod was pressed at temperature of 270 ℃ in the first pass. The temperature was decreased by 20 ℃ for each subsequent pressing. The temperatures were monitored and controlled to within ± 5 ℃. For each subsequent pressing the sample was held at temperature for about 10 min. The number of passes was 1, 4 and 8. The samples coated with molybdenum disulfide (MoS_2) were pressed at a pressing speed of 5 mm/min using route C [7] (i.e. the samples rotation of 180° after each pressing). The total strain rate, ε_n, in the specimen after N passes can be estimated as [13–15]

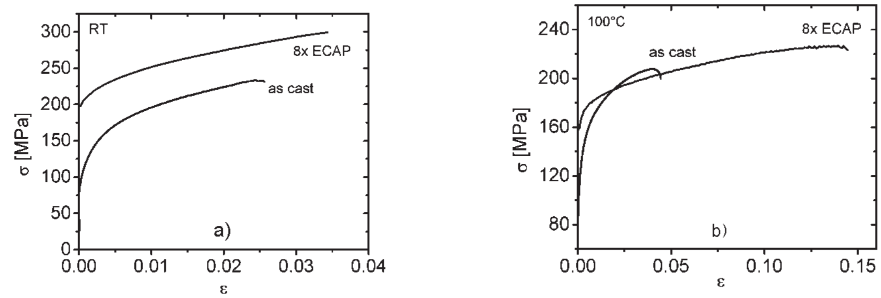
$$\varepsilon_n = 1.15 N \operatorname{cotg} \frac{\phi}{2}, \tag{1}$$

where Φ is 90°. The values of the total strain were 1.15, 4.6 and 9.2. The average grain size was between 0.5 and 1 μm.

Tensile specimens were machined from the rods produced by ECAP and they had a rectangular cross section of 1×2 mm^2 and the gauge length of 10 mm. Tensile tests were carried out in a MTS machine in the temperature range from 20 to 300 ℃ at a constant crosshead speed giving an initial strain rate of 5×10^{-4} s^{-1}.

3. Results and discussion

Figure 1 shows the true stress-true strain curves for both the as-cast AZ91 and the ECAP processed (eight-passed) AZ91 specimens deformed at various temperatures. It can be seen that the ECAP procedure has a significant effect on the elongation to fracture of specimens. The elongation to failure of the pressed AZ91 alloy is much higher than that of the unpressed alloy. It increases with increasing temperature. This is also confirmed in Fig. 2, which plots the elongation to failure against the test temperature. Plots of the true stress versus true strain are shown in Fig. 3 for AZ91 alloy after one, four and eight passes tested at 300 ℃. It is evident from these curves that the elongation to failure of the specimens increases with increasing pass number. After one pass, the yield stress is significantly lower than that of unpressed specimen [16]. The true stress versus true strain curves at



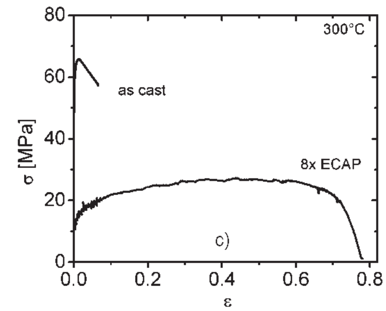


Fig. 1. True stress-true strain curves of as cast AZ91 and eight-passed AZ91 specimens deformed at various temperatures: a) room temperature, b) 100 °C and c) 300 °C.

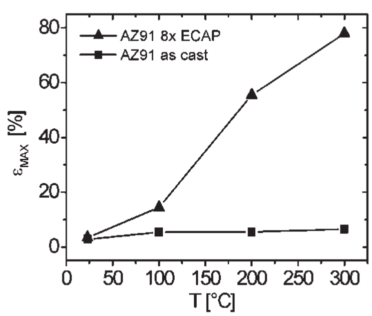


Fig. 2. Elongation to failure versus the test temperature.

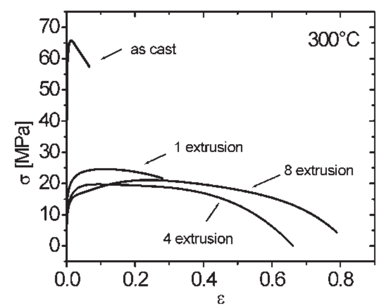


Fig. 3. True stress-true strain curves for unpressed and after one, four and eight passes (extrusions) AZ91 alloy specimens tested at 300 °C.

200 and 300 °C for the pressed AZ91 alloy show significant strain softening. In the previous paper [16], strain rate change experiments were used in order to estimate the strain rate sensitivity of the flow stress – m value – at 200 and 300 °C. The strain rate sensitivity of the flow stress was calculated using the equation:

$$m = \frac{\partial \ln \sigma}{\partial \ln \dot{\varepsilon}}, \tag{2}$$

where σ is the flow stress and $\dot{\varepsilon}$ is the strain rate. The mean values of m were 0.24 at 200 ℃ and 0.45 at 300 ℃, suggesting the superplastic behaviour above 200 ℃ ($\sim 0.51\,T_\mathrm{m}$, T_m being melting point of pure Mg) even if the elongation to failure is about 80 %. The values of the strain rate sensitivity parameters and the elongation to failure for the ECAP materials deformed at 200 and 300 ℃ may indicate the necessary conditions required for superplasticity in the AZ91 magnesium alloy. A high elongation to failure of 490 % at 250 ℃ and 10^{-3} s^{-1} was observed for AZ91 (the average grain size of 0.5 μm) by Mussi et al. [17]. Kubota et al. [18] have reported that the AZ91 alloy with the average grain size of 5 μm exhibits also a high elongation to failure of 340 % if deformed at 300 ℃ and 2×10^{-4} s^{-1}. The average grain size in the specimen used in this study was about 1 μm.

In comparison to as-cast (unpressed) specimens, there is a significant increase in the strength of AZ91 specimens after eight passes through the ECAP die if the specimens were deformed at room temperature. The yield stress of the one-passed AZ91 alloy deformed at 300 ℃ is lower than that of the as-extruded (unpressed) specimens – a decrease from about 58 to 15 MPa. The yield stress does not, practically, change as the pass number increases. The maximum stress exhibits a similar variation with the pass number [16]. Most probably, the values of the yield stress and the maximum stress are saturated after four passes [16].

It is evident from the stress-strain curves (Fig. 1) that there is a significant decrease in the yield stress and the maximum stress. The yield stress σ_{02} (the values of the 0.2 % proof strain) and the maximum stress σ_max are strongly depending on the test temperature as recorded in Figs. 4 and 5. It is interesting to note that both the yield stress and the maximum stress are higher for the ECAP processed specimens up to 100 ℃. Above this temperature a strong degradation of mechanical properties takes place and the values of σ_{02} and σ_max are higher for the as-cast material. The lower values of the yield stress and the maximum stress after

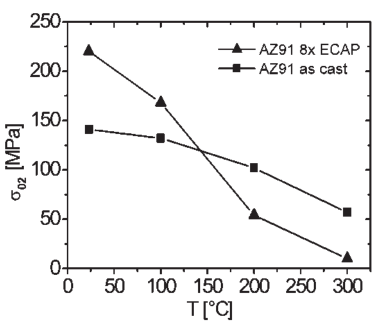


Fig. 4. Variation of the yield stress with the test temperature.

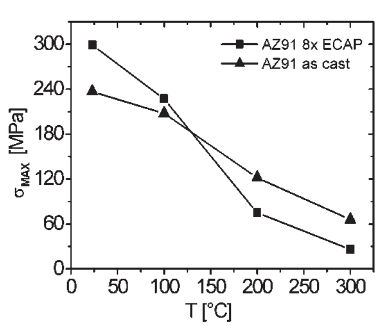


Fig. 5. Variation of the maximum stress with the test temperature.

ECAP indicate some recovery processes at 200 and 300 ℃. At the same temperatures, the stress-strain curves of the ECAP specimens (Fig. 1) demonstrate also the occurrence of significant strain softening in these specimens. The activity of non basal slip systems may decrease the flow stress and hence cause strain softening [2]. Grain boundary sliding in ECAP processed specimens at higher temperatures should be taken in account. Very probably $Al_{12}Mg_{17}$ precipitates could be sheared during each ECAP pass. At temperature larger than 200 ℃, the precipitates are soft and could be also dissolved [19] and, therefore, a softening can occur.

4. Conclusions

The use of ECAP provides an effective procedure for improving the mechanical properties of AZ91 alloy. The strength is increased at room temperature and 100 ℃ because the grain size is lower than in commercially used AZ91 alloy. The ductility increases because more grains contribute to the macroscopic deformation. The strain softening observed at 200 and 300 ℃ and the large elongation to failure in ECAP specimens indicate the activity of basal and non basal slip systems.

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