DEFORMATION BEHAVIOUR OF AZ31 MAGNESIUM ALLOY

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Abstract

It is shown that the deformation behaviour of AZ31 alloy polycrystals depends on their microstructure, including texture, and temperature. The tensile tests were conducted over a wide temperature range of 25 and 300 °C at a constant strain rate. The rolled (textured) samples exhibit anisotropy in the mechanical properties i.e. the yield stress of the samples with tensile axis parallel to the rolling direction is lower than that of the samples deformed perpendicular to the rolling direction. The plots of the work hardening rate against flow stress indicate interaction between basal and non-basal slip systems. The internal stress, estimated using the stress relaxation tests, decreases with increasing deformation temperature, which indicates recovery processes that play an important role during deformation at elevated temperatures. Analysis of the strain hardening rate as a function of applied stress at different temperatures and the estimation of the internal stress as a function of deformation temperature enable to determine the activity of deformation mechanisms: (a) interaction between dislocations in basal and non-basal slip systems may produce sessile and glide dislocations and (b) cross slip of dislocations causing softening.

Keywords: Deformation; Strain hardening; AZ31 alloy; Polycrystals

1. INTRODUCTION

Most magnesium alloys exhibit a relatively high specific strength (the strength/density ratio) at room temperature due to their low density. On the other hand, the mechanical properties of many magnesium alloys at elevated temperatures are poor. Their mechanical properties have been estimated at various temperatures as a function of the composition, grain size, and thermal treatment. Their disadvantage is limited formability connected with their hexagonal close-packed (hcp) structure. The main (easy) glide systems in Mg and its alloys are basal slip systems i.e. motion of \(<c+a>\) dislocations in the basal plane in one of two independent directions. However, five independent deformation modes are necessary for homogeneous plastic deformation of a polycrystal, according to the von Mises criterion [1]. Likewise, the strain to failure in tension in Mg alloys at room temperature is much lower than that in some Al alloys. This can also be ascribed to the fact that the von Mises criterion requiring five independent slip modes cannot be met. An improvement in ductility may be owing to the activity of non-basal slip systems and/or deformation twinning [2-5]. The second-order pyramidal slip systems, \(\{1\bar{1}20\} \langle\bar{T}T\bar{2}3\rangle\), that have dislocations with the Burgers vector \(<c+a>\), are considered as significant. These slip systems offer five independent slip systems. The critical resolved shear stresses (CRSS) for non-basal slips at room temperature are much higher than that for basal slip. However, they decrease very rapidly with increasing temperature. Twinning may also accommodate strain along c axis. The CRSS for \(<c+a>\) slip (and/or prismatic slip) may be lowered by alloying with small amounts of some alloying elements. The activation of second-order pyramidal slip systems with glide of \(<c+a>\) dislocations is expected to be easier at elevated temperatures. Only few studies are dealing with the investigations of the deformation behaviour. From these studies it follows that the deformation behaviour of magnesium alloys depends on many parameters as alloy composition,
microstructure, grain size, temperature, strain rate, texture, and deformation mode. Investigations of the influence of temperature are important for applications and for estimation of suitable forming conditions. In order to understand the flow behaviour of a material, it is important not only to estimate the experimental values of the deformation characteristics but also to determine the dislocation mechanisms responsible for deformation. It should be noted that the stress-strain curves of a polycrystal the strain hardening rate are significantly influenced by storage and annihilation of dislocations and changes in the texture. The yield stress values of textured materials are higher than those for isotropic ones and are usually different in different loading directions. The aim of this paper is to show the effect of temperature on the deformation behaviour of AZ31 magnesium alloy prepared by two different processes and to describe dislocation mechanisms that control the behaviour.

2. EXPERIMENTAL PROCEDURE

In this study we used AZ31 alloy (nominal composition Mg-3Al-1Zn in mass%) prepared by cast and warm-rolled conditions. The magnesium alloy AZ31 sheets were in the stress-relieved (H24) temper. Samples of cast alloy for tensile tests having a cylindrical form with a diameter of 5 mm and a gauge length of 25 mm were deformed using an INSTRON tensile machine at a constant cross head speed giving an initial strain rate of 3x10^{-5} s^{-1}. Tensile specimens of AZ31 sheets with a gauge length of 25 mm, 5 mm width and 1.6 mm thickness were also deformed in an INSTRON tensile machine at an initial strain rate of 1.3x10^{-3} s^{-1}. Some sheet specimens were annealed at 300 °C for 8 h in order to obtain an alternative state with the lower preliminary hardening due to stored dislocations and twin boundaries (hereafter referred to as 300/8 or A). For sheet specimens, tensile tests with load axis parallel (hereafter R specimens) and perpendicular (transversal direction, hereafter T specimens) to the rolling direction were conducted. Tensile tests were carried out at various temperatures between room temperature and 300 or 400 °C. The temperature in furnace was controlled to within ±2 °C.

3. RESULTS AND DISCUSSION

The true stress-true strain curves for the cast AZ31 alloy obtained in tension at different temperatures are shown in Fig. 1. The true stress-true strain curves of the AZ31 sheets in H24 condition (hereafter H24) with the tensile axis parallel to the rolling direction obtained at various temperatures are given in Fig. 2 [6]. It can be seen that the shape of the stress-strain curves is very sensitive to the testing temperature. The flow stress decreases and the elongation to fracture increases with increasing temperature. The results indicate that dynamic recovery occurs. Two flow curves of the sheets deformed at 100 and 200 °C presented in Fig. 2

![Fig. 1: Stress-strain curves obtained for various temperatures.](image1)

![Fig. 3: Temperature dependence of the yield and maximum stresses.](image2)
show small scatters in the elongation to fracture. At higher temperatures, above about 250 °C, the flow stress is practically independent of strain. i.e. no significant strain hardening is observed. A dynamic balance between hardening and softening occurs. It can also be seen that processing methods influence the value of the flow stress. The values of the yield strength, $\bar{\sigma}_{0.2}$, determined as the flow stress at 0.2% offset strain and the maximum flow stress, $\bar{\sigma}_{\text{max}}$, determined as the maximum flow stress are plotted against temperature in Fig. 3 and Fig. 4 [6] for the cast AZ31 and AZ31 sheets, respectively. Figure 3 shows a moderate decrease of the yield strength and a rapid decrease of the maximum stress. On the other hand, both the yield strength and the maximum stress of AZ31 sheets decrease rapidly with a temperature increase. The values of the yield stress and maximum stress for AZ31 sheets are higher than those of cast AZ31 samples deformed at the same temperature. The difference is cause by a lower grain size of the sheets and first of all by a higher dislocation density in the sheets due to their fabrication (rolling).

![Fig. 2: Tensile curves for initial state H24 and tensile axis R][6].](image1)

![Fig. 4: Yield and maximum stresses for initial state H24 and tensile axis R][6.](image2)

The deformation behaviour is significantly influenced by temperature. It should be mentioned that similar stress-strain curves as in this work have been reported for Mg-Al-Ca and Mg-Al-Sr alloys i.e.g. AX41, AX91, AJ51 and AJ91 [7]. At temperatures above about 200 ñ 250 °C the strain hardening is very close to zero. Hardening is compensated for by recovery. We may assume that the flow stress, $\bar{\sigma}$, depends on the average dislocation density, $n$, as $\bar{\sigma} \sim \sqrt{n}$. The flow stress and the strain hardening rate change with strain as a result of changes in the dislocation structure with plastic deformation. Dislocations stored (at obstacles) contribute to hardening. On the other hand, dislocations may cross slip and/or climb. After double cross slip and/or climb, dislocations may annihilate and hence, the total dislocation density decreases, which causes a decrease in the strain hardening i.e dynamic recovery (and or dynamic recrystallization) may take place. Under some conditions, a dynamic balance between hardening and softening may occur. Figure 5 shows the true stress-true strain curves for the sheets deformed after annealing at 300 °C for 8 h (A) and for the sheets in the H24 condition [8]. The specimens were deformed with tensile axis parallel to the rolling direction. The results demonstrate that the effect of temperature on the deformation behaviour of both specimen types is
Balík et al. [6] have reported that the values of the yield strength are lower for the annealed sheet. This was caused by a decrease of the dislocation density and the volume fraction of twins. The effect of the tensile direction with respect to the rolling direction on the deformation behaviour was investigated in our previous paper [6].

The strain hardening may be analysed using a plot of the strain hardening rate, $\dot{\varepsilon}$, against the flow stress. This is shown for specimens in both an aged state and an H24 state (deformed at 25 and 100 °C) in Fig. 6. Breaks in the $\dot{\varepsilon}$ vs $\dot{\varepsilon}$ plots for the 380/8 AZ31 sheets, accompanied by a lift in the strain hardening rate, are observed. The lifts were also observed at 150 and 200 °C independent of the tensile direction in respect to
the rolling direction [8]. We assume that these lifts are connected with the activity of non-basal slip rather than twinning. The stress dependences of the strain hardening rate at different temperatures enable to analyse hardening and softening processes, as has been shown by Máthis et al. [9] for AM60 magnesium alloy and by Wu and Lin [10] for AZ31 sheets. The activity of non-basal slip system has to play an important role in both hardening and softening processes. The glide of \(<c+a>\) dislocations is responsible for strain hardening because immobile or sessile dislocations may be created. The activity of the second-order pyramidal slip systems with the \(<c+a>\) dislocations may contribute to softening because mobile or glissile dislocations can also be formed. Different reactions between \(<a>\) dislocations and \(<c+a>\) pyramidal dislocations can occur [2, 3, 6]. Dislocation reactions may produce both sessile and glissile (glide) dislocations. Grain boundaries and twins are also obstacles for moving dislocations. The stress concentration at the head of the dislocation pile-ups formed at grain boundaries decreases the resolved shear stress necessary for the activity of non-basal slip systems. The resolved shear stress may be lower than the CRSS for the non-basal slip system and it is decreasing with temperature. An increase in the activity of non-basal slip system with increasing temperature contributes to the enhanced ductility observed with the temperature increase. On the other hand, screw components of both \(<a>\) and \(<c+a>\) dislocations may move to the parallel slip planes by double cross slip and they can annihilate. This leads to softening. A fraction of dislocations may also be annihilated by climb of dislocations with jogs. The activity of both cross slip and climb increases with increasing temperature. The effect of both cross slip and climb of dislocations on the stress dependence of the strain hardening rate were considered by Lukáč and Balík [11].

4. CONCLUSIONS

The testing temperature influences significantly the deformation behaviour of AZ31 alloy independent of fabrication. At temperatures below 200 ÷ 250 °C, hardening occurs. A dynamic balance between hardening and softening (the strain hardening rate close to zero) takes place at temperatures higher than 200 ÷ 250 °C. The AZ31 sheets in the state after ageing at 300 °C for 8 h exhibit lower flow stress than their counterparts in the H24 state. The early break/lifits in the course of the stress dependence of the strain hardening rate of the annealed sheets are likely connected with dislocation glide in the second-order pyramidal slip systems. Glissile and sessile dislocations are created by an interaction between basal and non-basal slips. The double cross slip of screw components of both \(<a>\) and \(<c+a>\) dislocations may cause annihilation of dislocations leading to softening.

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