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# MECHANICAL PROPERTIES OF AZ91 MAGNESIUM ALLOYS

*Commercial magnesium alloys AZ91 were reinforced with $Al_2O_3$ short fibres. The composites were prepared by different fabrication routs (powder metallurgy technique, squeeze casting and casting followed by extrusion). Some specimens of the AZ91 alloy were prepared using equal channel angular pressing. The values of the yield stress and the maximum stress of specimens deformed at temperatures between 20 and 300 °C were determined. The test temperature strongly influences the mechanical properties of the AZ91 alloy and its composites.*

## 1. Introduction

Engineering importance of magnesium alloys has grown recently. The automotive industry shows a growing interest in magnesium alloys because of their low density and high damping. Magnesium alloys as a structural material in cars may reduce fuel consumption and exhaust emissions. The applications fields for magnesium alloys are also aviation and communication industries. Magnesium alloys are considered as promising light structural materials, even if they have poor ductility. If deformed at room temperature, they exhibit a tensile elongation of only a few percent. Among the most commercial magnesium alloys used, AZ91 alloy (Mg-9Al-1Zn) dominates. The mechanical properties of the commercial magnesium alloy AZ91 depend strongly on temperature. The specific strength of AZ91 at room temperature is high but it remains rather low at temperature above about 120 °C. It is well known that it is a close relationship between microstructure and the mechanical properties. In order to improve the mechanical properties it is important to understand the deformation mechanisms of yielding and work hardening. Solid solution hardening, precipitation and/or dispersion strengthening influence the yield stress. The yield stress increases also with decreasing grain size. The grain size dependence of the yield stress and tensile strength can be expressed by the Hall – Petch relation. Magnesium alloys reinforced with short ceramic fibres or particles exhibit significantly higher mechanical properties than conventional alloys. The microstructure of alloys and metal matrix composites is influenced by the fabrication routs. The mechanical properties and the deformation behaviour of Mg alloys as well as composites are strongly influenced by temperature and strain rate. The aim of this paper is to provide information on the mechanical properties of AZ91 alloys and AZ91+Saffil composites deformed at various temperatures. The results will be discussed.

## 2. Experiments

The investigated materials were AZ91 (9Al, 0.7Zn, 0.2Mn in wt.%) alloy and AZ91 reinforced with $\delta$-$Al_2O_3$ short fibres (Saffil$^{®}$) with a mean diameter of 3 $\mu$m and a mean length about of 87 $\mu$m. Alloys were prepared by different fabrication routs. Composites were prepared by squeeze casting. The preforms, consisting of $Al_2O_3$ short fibres with a planar isotropic fibre distribution, were infiltrated using two-stage application of the pressure. Tensile specimens of the cylinder form with a gauge length of 25 mm (with a diameter of 4 mm) and compression specimens with dimensions $5 \times 5 \times 10$ mm$^3$ were annealed according to T6 treatment (413 °C/18h, then 168 °C/8h). Tensile and compression tests were carried out using an Instron machine at temperatures between 22 and 300 °C at a strain rate of $8.3 \times 10^{-5}$ s$^{-1}$. Some tensile specimens with dimensions of $1 \times 2 \times 10$ mm$^3$ were machined from the rods produced by equal channel angular pressing (ECAP).

## 3. Experimental results and discussion

The value of the yield stress (YS = 0.2 % proof stress), tensile strength (UTS) and the % elongation to fracture (A) of AZ91 alloys and composites produced by various fabrication routs are given in Table 1 (for specimens deformed at room temperature and 200 °C). Above 100 °C the yield stress and tensile strength of AZ91 alloy decrease very rapidly with increasing temperature. The elongation to fracture increases with increasing temperature. Aune and Westengen [1] have reported that the elongation to fracture is 7 % at room temperature and it reaches 13 % and 23 % at 100 °C and at 150 °C, respectively. Table 1 shows that the values of the yield stress of AZ91 alloys and AZ91/$Al_2O_3$ composites [2, 3] are influenced by the fabrication methods. Composites (AZ91 + 15 vol. % Saffil) and also matrix alloys prepared by powder metallurgy (PM) exhibit a higher tensile strength and a higher yield stress than those materials prepared by squeeze casting (Sc) and casting followed by extrusion (Sce). The reason for the increase in the mechanical properties is an increase in the dislocation density induced by the powder metallurgy technique or extrusion process. The increased dislocation density causes a decrease in the dislocation mobility. The free path of dislocation is lower. This may induce an enhanced ductility of AZ91 materials prepared by squeeze casting. However, it should be noted that squeeze casting is more suitable for preparation of short fibre reinforced composites because of less damage of the fibres in com-

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parison to the PM technique. It is important to note that while the yield stress and tensile strength of composites prepared by squeeze casting decrease gradually with increasing temperature, the same tensile properties of composites prepared by PM decrease strongly with increasing temperature. The addition of the fibres to the matrix increases both the yield stress and tensile strength.

Tensile properties of unreinforced and reinforced AZ91 alloy at room temperature Tab. 1

| | YS/MPa | UTS/MPa | UTS/MPa at 200 °C | A/% |
|---|---|---|---|---|
| AZ91 (PM) | 270 | 330 | 120 | 4.0 |
| AZ91 + 15 (PM) | 395 | 420 | 123 | 0.7 |
| AZ91 (Sc) | 120 | 230 | 120 | 8.5 |
| AZ91 (Sce) | 240 | 325 | 132 | 4.0 |
| AZ91 + 20 (Sc) | 245 | 320 | 227 | 1.8 |
| AZ91 + 20 (Sce) | 282 | 290 | 147 | 0.7 |

The deformation behaviour (see the differences in the values between tensile strength and yield stress) is influenced by the thermal stresses. Cooling of a composite from a higher temperature of processing to room temperature may generate thermal residual stresses due to the difference in the coefficients of thermal expansion (CTE) of the matrix and reinforcement. If the applied stress is zero, then the thermal stress near the interface between reinforcement and matrix is given by

$$\sigma_{TS} = E_f E_m f \Delta\alpha \Delta T / [E_f f + (E_m(1 - f)] \quad (1)$$

where $f$ is the volume fraction of fibres, $\Delta\alpha$ is the CTEs difference, $\Delta T$ is the temperature range, $E_f$ and $E_m$ are the elastic modulus of the fibres and the matrix, respectively. If thermal stresses become larger than a critical stress, stress relaxation occurs and new dislocations are generated at the interface (in the matrix near the fibres). The density of newly created dislocations produced by the thermal stresses in the composite reinforced with fibres can be calculated as [4, 5]

$$\Delta\rho = Bf \Delta\alpha \Delta T / (1 - f) br \quad (2)$$

where $B$ is a constant that depends on the geometry of the fibres, $r$ is their radius and $b$ is the magnitude of the Burgers vector. The increase in the flow stress corresponding to the increase in the dislocation density is given by

$$\Delta\sigma = \mathrm{AGb}(\Delta\rho)^{1/2} \quad (3)$$

where $A$ is a constant and $G$ is the shear modulus of the matrix. The increase in the flow stress of the matrix in the composite over unreinforced metal is proportional to square root of $\Delta\alpha\Delta T$, if the newly generated dislocations due to CTE mismatch are dominant. In any cases, a dislocation increment due to CTE mismatch and cooling is one of strengthening mechanisms in the composites. The dislocation density near the interface is significantly higher than elsewhere in the matrix. Plastic zones containing tangled dislocations may be formed around the fibres. The dislocation movement is determined by the required stress that depends on temperature, the internal stress in the matrix, the distribution and kind of obstacles, and the crystallographic orientation of the grains to the fibres.

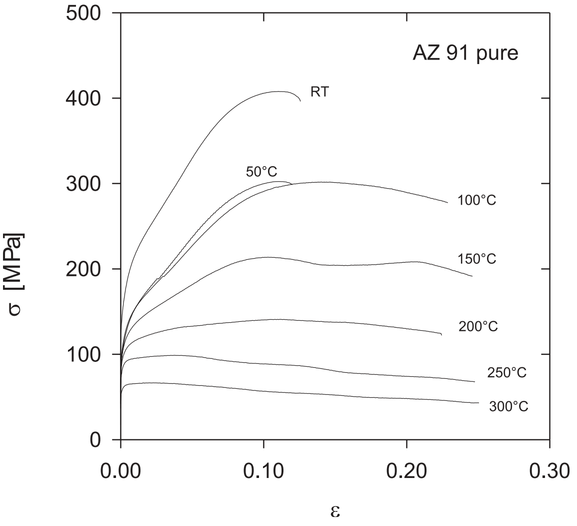

*Fig. 1 The true stress-true strain curves obtained in compression*

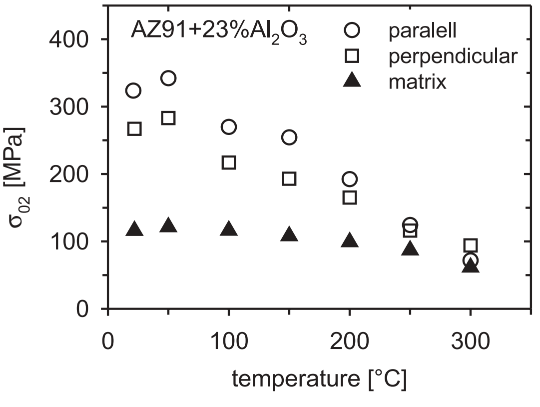

*Fig. 2 Temperature dependence of unreinforced AZ91 magnesium alloys and the alloys reinforced with 23-vol. % of $Al_2O_3$*

The influence of the test temperature on the stress strain curves of AZ91 alloy for a compression test is shown in Fig. 1. It can be seen that the flow stress and the strain hardening decrease significantly with increasing temperature. At temperatures above about 250 °C strain softening is observed from the very beginning of deformation. The temperature dependence of the yield stress $\sigma_{02}$ (defined as the flow at 0.2 proof strain) of AZ91 alloy deformed in compression is shown in Fig. 2. Similar variation of the maximum stress with temperature was obtained (Fig. 3). Between 100 and 200 °C, the decrease in the yield stress is slow. It is interesting to note that the strain (elongation) at which the maximum tensile stress is reached decreases with temperatures above 100 °C. Dynamic recovery is observed for AZ91 specimens deformed at temperatures above 100 °C (see Fig. 1). The stress strain curves of AZ91+23 vol.% Saffil estimated in the same temperature range have similar forms as those for unreinforced alloy. The yield stress values of the composites deformed in compression are higher than those for specimens deformed in tension. The temperature dependence of the yield stress of the composite deformed in compression is also shown in Fig. 2. Planes with planar randomly distributed fibres were parallel with or perpendicular to the specimen axis (applied stress). The yield stress decreases strongly with increasing temperature. The reduction in the yield stress of the composite with temperature is higher than that of the alloy. It can be seen that short fibres and the distribution of planes with fibres influence the strength of composites. Figure 3 shows the temperature dependence of the maximum stress of unreinforced and reinforced AZ91 alloys. The strengthening effect is influenced by temperature; it decreases with increasing temperature.

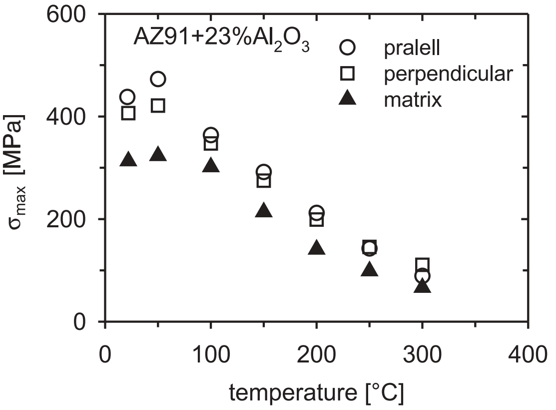

*Fig. 3 Temperature dependence of the maximum stress of unreinforced AZ91 alloy and the alloy reinforced with 23-vol. % of $Al_2O_3$*

As mentioned above, a reduction of the mean grain size is expected to increase the yield stress of a material at room temperature (the Hall – Petch relationship). In ECAP process, the material is subjected to severe plastic deformation that may be approximated to simple shear. Very high strains may be achieved, which leads to a substantial grain refinement and to an increase in the dislocation density. In the previous paper [6], the effect of the ECAP procedure on the deformation behaviour of AZ91 magnesium alloy was investigated at various temperatures at an initial strain rate of $5 \times 10^{-4}$ s$^{-1}$. The yield stress and the maximum stress are strongly depending on the test temperature as shown in Figs. 4 and 5. It is obvious that both the yield stress and the maximum stress are higher for the ECAP processed specimens (after eight passes) up to 100 °C. Above this temperature a strong decrease of both stresses is observed. Above 100 °C the values of both the yield stress and the maximum stress are higher for the as-cast material (without ECAP processing). On the other hand, the elongation to fracture of the pressed AZ91 alloy specimens is increasing with increasing temperature above 100 °C. The elongation to fracture of AZ91 specimens after ECAP procedure is much higher than that of unpressed alloy. The elongation to fracture of specimens after eight passes in ECAP procedure deformed at 300 °C is about 80 %. The refinement of grains and a high testing temperature may explain this behaviour. A reduction of the mean grain size of AZ91 alloy after the ECAP procedure increases the yield stress and the maximum stress at room temperature according to Hall-Petch relationship. The temperature of 100 °C (373 K) corresponds to 0.4 $T_m$, $T_m$ being the absolute melting temperature. At this temperature, an increase in the diffusion activity may be expected. Grain boundary sliding in the ECAP processed specimens (the mean grain size was between 0.5 and 1 $\mu$m) should be considered. Kubota et al. [7] have reported that the AZ91 alloy with the grain size about 5 $\mu$m exhibits a large elongation to fracture of 340 % if deformed at 300 °C and at strain rate of $2 \times 10^{-4}$ s$^{-1}$. Mabuchi et al. [8, 9] have reported that AZ91 alloy after the ECAP procedure (the mean grain size of about 1 $\mu$m) exhibits a large elongation to fracture of 661 % if deformed at 200 °C and at strain rate of $6 \times 10^{-5}$ s$^{-1}$. These high values of the elongation to fracture indicate the superplastic behaviour, in which grain boundary sliding plays a significant role. At higher temperatures, larger than 200 °C, the activity of non basal slip system increases. (The activity of five independent slip systems is required for

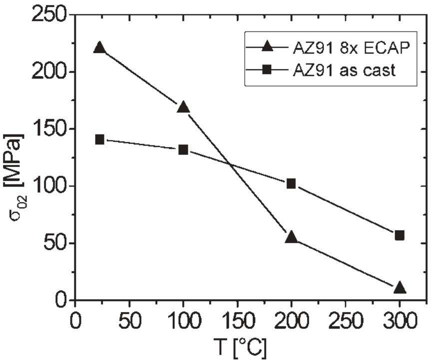

*Fig. 4 Temperature dependence of the yield stress of AZ91 alloy and the alloy after ECAP procedure (eight passes)*

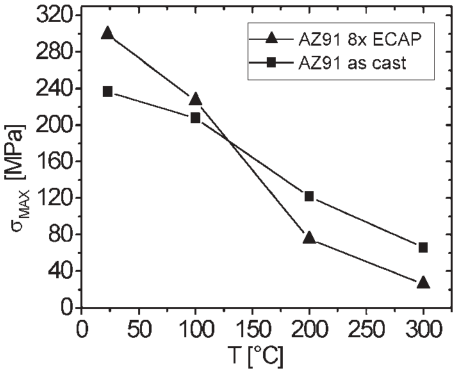

*Fig. 5 Temperature dependence of the maximum stress of AZ91 alloy and the alloy after ECAP procedure (eight passes)*

plastic deformation of polycrystals.) In Mg and Mg alloys, where the main slip system is the basal one, the second order pyramidal slip systems may be active at temperatures above 150 – 200 °C. Not only an interaction between a and ***c* + *a*** dislocations but also among the pyramidal ***c* + *a*** dislocations can take place [10]. Different dislocation reactions can take place. Some dislocation reactions may produce obstacles for the moving dislocations. Other dislocation reactions may result in annihilation of dislocations, and therefore, cause strain softening. The macroscopic work hardening rate is a sum of hardening due to storage of dislocations at obstacles and softening due to annihilation of dislocations. During deformation, the moving dislocations can cross slip. Screw dislocations can move to the parallel slip planes by double cross slip and then may annihilate. The probability of cross slip increases with increasing temperature. Edge dislocations can climb at high temperatures. The higher temperature the more dislocations can climb. The dislocation annihilation may take place and hence, softening occurs. The changes in the shape of the stress strain curves with increasing temperature may be accounted for by considering of softening mechanisms above mentioned.

## 4. Conclusions

Commercial AZ91 magnesium alloys and composites with the matrix of AZ91 lose their strength at temperatures above 150 – 200 °C. They are unusable for structural application. The experimental results clearly demonstrate the significant role of temperature on the deformation behaviour of unreinforced and reinforced AZ91 alloys. The shape of the stress strain curves indicates that hardening at higher temperatures is influenced by recovery processes. Cross slip and local climb of dislocations can be regarded as possible softening mechanisms. The fibres added to the matrix increase both the yield stress and the tensile strength. The AZ91 alloys prepared by ECAP procedure exhibit higher strength at room temperature in comparison with those alloys prepared by squeeze casting. Above 200 °C, the lower strength and larger elongation of AZ91 alloys prepared by ECAP in comparison with those alloys after squeeze casting is believed to be mainly due to the occurrence of softening mechanisms. Grain boundary sliding cannot be excluded at higher temperatures, at which the superplastic deformation may be expected.

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