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Deformation behaviour of ZC63 magnesium matrix composite

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ABSTRACT

Purpose: of this paper is to give information on the deformation behaviour of ZC63 magnesium alloys reinforced with 10 vol. % of SiC particles.

Design/methodology/approach: The deformation behaviour of the ZC63/10SiCp composite was investigated in tensile tests over the temperature range from 23 to 200 °C at an initial strain rate of 8.3 x 10^{-3} s^{-1}.

Findings: The flow stress decreases with increasing temperature. Both the yield stress and the maximum stress decrease with increasing temperature for temperatures higher than 100 °C.

Research limitations/implications: The paper indicates significant softening mechanisms that take place at high temperature deformation.

Practical implications: The ZC63/10SiCp composite may be used for applications at temperatures above 100 ºC.

Originality/value: New results on the temperature dependence of the yield stress and maximum stress were obtained.

Keywords: Composite; Magnesium alloy; Mechanical properties; Dislocation mechanisms

MATERIALS

1. Introduction

Magnesium alloys are potential candidates for many structural applications due to their relative high specific strength (strength/density ratio) at room temperature. However, main disadvantages of magnesium alloys are their mechanical properties at elevated temperatures. A rapid decrease of the yield stress and tensile strength occurs above 100°C [1-10]. An increase in the strength may be achieved by reinforcement. Metal matrix composites (MMCs) can provide a substantial increase in the strength. As prospective light construction materials Mg-based MMCs reinforced by short ceramic fibres (Saffil®, carbon) and/or particles (SiC, B_4C, Al_2O_3) have been developed and manufactured in recent years in order to attain properties not available for conventional alloys [11-13]. Magnesium and its alloys reinforced with SiC particles are of great interest because the reinforcement may lead to significant improvement in stiffness and strength. SiC particles are stable in pure magnesium, and no reaction products were observed in pure magnesium reinforced by SiC particles [14]. The effect of SiC particles on the matrix-particles interfaces was also studied in QE22 (Mg-2Ag-2RE) matrix alloy [15]. In the SiC-reinforced AZ91, however, particle/matrix interface reactions are evidenced by the presence of Mg_2Si phase [16]. Significant improvement of the yield stress of the composite over the unreinforced AZ91 alloy has been achieved. The Mg_2Si products are also formed around the SiC particles in QE22/SiC composite [11]. Extensive precipitation of Nd rich phases ($Mg_{12}Nd$) at the SiC/matrix interface in QE22/15 vol.% SiC composite after T6 treatment was found by Pahutová et al. [17]. The values of the yield stress and the tensile strength of the reinforced QE22 alloy are higher than those for the unreinforced alloy. On the other hand, Chmelík et al. [15] have reported that the creep rate of QE22 alloy reinforced with 15 vol.% SiC particles is significantly higher than that of the unreinforced specimens at 200°C. This behaviour may be explained by considering interfacial sliding and by grain refinement owing to the presence of the SiC particles. In

ZC63/SiC composite, Mg_2Si particles were detected at the matrix/SiC interface. It is well known that in composites, there is a large difference in the coefficients of thermal expansion (CTE) between the matrix and the reinforcement. When a metal matrix composite is cooled from a higher temperature to room temperature, misfit strains occur at the interface owing to different contraction of both components. These strains induce thermal stresses that can be generally expressed in the following forms:

$$\sigma_{TS} = f(C,r_i)\Delta\alpha\Delta T, \qquad (1)$$

where $f(C,r_i)$ is a function of the elastic constants C and geometrical parameters r_i, $\Delta\alpha$ is the difference in the values of the thermal expansion coefficients and ΔT is the temperature change. The induced thermal stresses may be higher than the yield stress of the matrix and may generate new dislocations at the interfaces between the matrix and the reinforcement. An increase in the dislocation density $\Delta\rho$ due to the newly formed dislocations at the interfaces has been calculated [18, 19] as

$$\Delta\rho = \frac{Bf\Delta\alpha\Delta T}{b(1-f)t}, \qquad (2)$$

where B is a geometrical constant, b is the Burgers vector of dislocations, f is the volume fraction of the reinforcement and t is its minimum size. Mg-Zn-Cu alloys were developed for a combination of good ductility at elevated temperatures performance, where Cu imparts grain refining effect and Zn good castability and ductility [2]. The objective of the present work is to investigate the influence of temperature on the deformation behaviour of ZC63 magnesium alloy reinforced with 10 vol. % of SiC particles.

2. Experimental procedure

The materials used for this study were magnesium alloy ZC63 (nominal composition in wt% Mg-6Zn-2.7Cu-0.5Mn) reinforced with 10 vol. % of SiC particles. Materials were prepared by squeeze casting (two-stage application of the pressure). The β-SiC particles were available as bulky particles with large planar faces and sharp boundaries.

Tensile tests were performed in an INSTRON testing machine at a constant crosshead speed giving an initial strain rate of 8.3×10^{-3} s^{-1} at temperatures between room temperature and 200 °C. Cylindrical specimens had a gauge lengths of 25 mm and diameters of 5 mm. Four tests were performed at each temperature.

3. Experimental results

Microscopic examinations of the ZC63/SiC composite have shown more or less uniform grain structure associated with the dendrites. The reinforcing particles are segregated in the inter-dendritic regions (Figure 1).

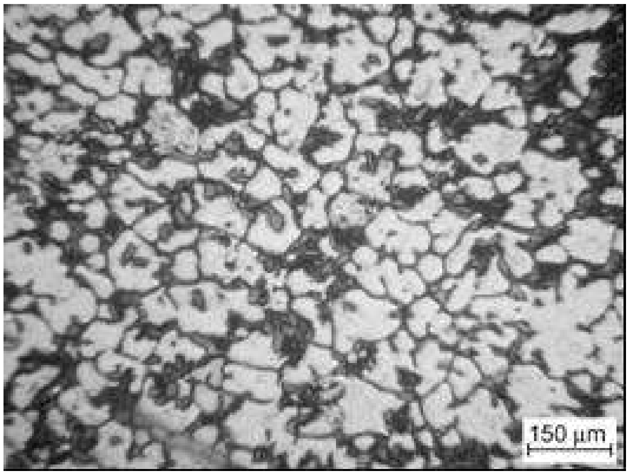

Fig. 1. Microstructure of the as cast ZC63 alloy

This microstructure did not change with the deformation temperature. Almost no defects and no products of chemical reaction between the matrix and particles were detected at the matrix/particle interfaces.

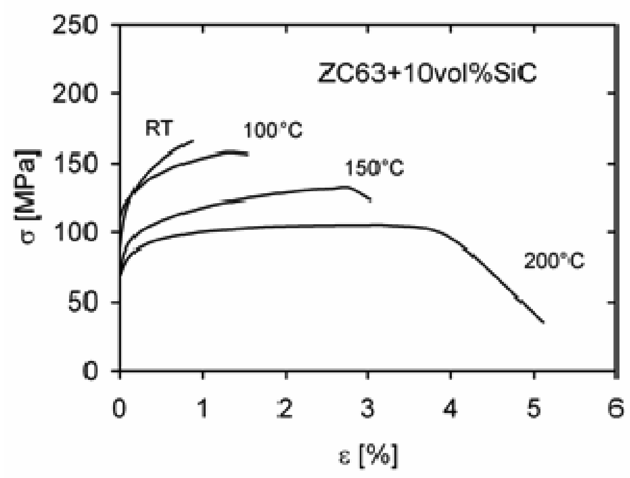

Fig. 2. True stress-true strain curves

It is interesting to note that the microstructure of AS41/SiC composite exhibits similar features with Mg_2Si precipitates on the grain boundaries.

Figure 2 shows typical true stress-true strain curves of the ZC63/SiC composite deformed at different temperatures. It can be seen that the flow stress decreases with increasing temperature. At 200 °C, the work hardening is close to zero. This indicates a dynamic balance between hardening and softening. The temperature variations of the yield stress σ_{02} (estimated as the flow stress at 0.2 % strain) and the tensile strength σ_{max} (defined as the maximum value of the flow stress) are given in Figure 3.

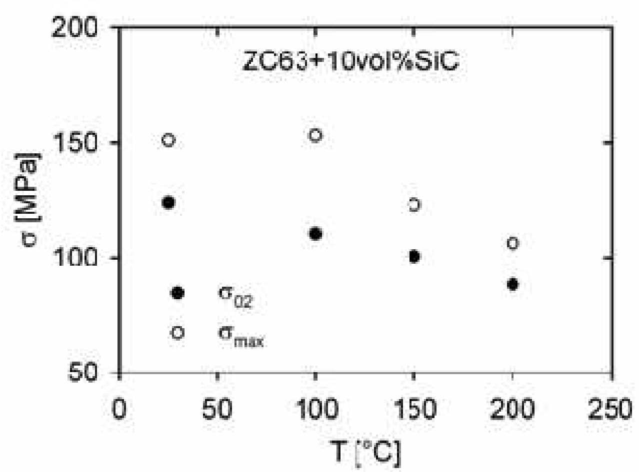

Fig. 3. Temperature dependence of the yield stress and the maximum stress

It can be seen that the yield stress and maximum strength decrease with increasing temperature for temperatures higher than 100 ºC. On the other hand the elongation to fracture ε_f in % increases with increasing temperature, as shown in Figure 4.

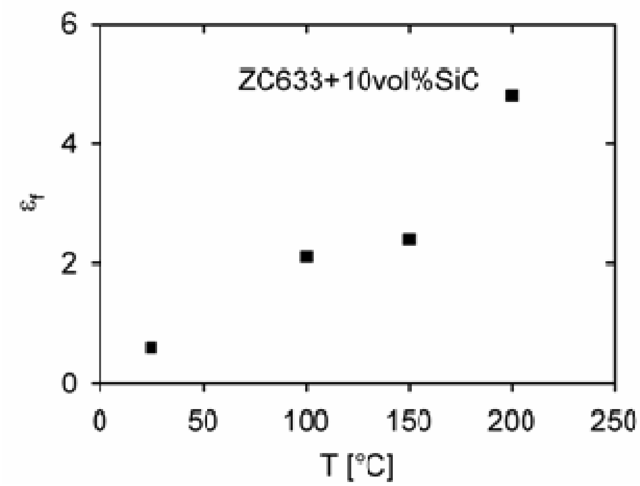

Fig. 4. Temperature dependence of the ductility

4. Discussion

As mentioned above, thermal residual stresses in MMC created due to the misfit strain may accommodate generating new dislocations at the matrid/reinforcement interfaces. Thus, the total dislocation density in the composite increases. It is higher than the total dislocation density in the unreinforced alloy. A high dislocation density and extensive twinning around particles has been observed in ZC63/SiC composites [20]. These dislocation substructures and stress fields around the particles are responsible for the preferential nucleation of precipitates [20].

In the composite investigated in this study, an increase in the dislocation density (due to newly generated dislocations) and precipitates nucleated during solidification process are also expected. The dislocations, precipitates and SiC particles are obstacles for the motion of dislocations. The stress necessary for the dislocation motion (required for overcoming of obstacles) must be higher than that for the dislocation motion in the unreinforced alloy. These obstacles are responsible for the observed increase in the yield stress of the composites. Impenetrable particles such as SiC particles in the metallic matrix can be passed by dislocations by the Orowan mechanism leaving loops behind. These loops contribute to the storage of dislocations and increase the stress. During straining, the particles can be overcome locally by cross slip. Work hardening reflects the way in which the arrays of stored dislocations are obstacles for moving dislocations. At higher temperatures, the work hardening rate is low, it is close to zero. Such a steady-state deformation occurring at higher temperatures is a result of a dynamic balance between storage of dislocations leading to hardening and annihilation of dislocations leading to softening. The processes of softening are thermally activated ones. The activity of non-basal slip systems plays an important role in the deformation behaviour of magnesium alloys and composites, especially at higher temperatures [21]. From the activities of the non-basal slip modes, motion of dislocation with (**c** + **a**) Burgers vector in the second-order pyramidal slip systems is expected. Different interactions between basal dislocations (**a** dislocations) and the pyramidal ones – (**c** + **a**) dislocations can occur and are responsible for the deformation behaviour. Dislocation reaction may produce sessile dislocations and an increase in the density of the forest dislocations. Therefore, additional obstacles of the dislocation type are formed and an increase in hardening should result. Screw dislocations of (**c** + **a**) type can move to the parallel planes by double cross slip and then annihilate. The local climbing mechanism with subsequent annihilation of dislocations may also decrease the dislocation density and a decrease of the internal stress can follow. The decrease in the dislocation density due to annihilation recovers the matrix, which causes a decrease in the work hardening rate. The deformation process proceeds in its steady state form. An increase in ductility of the composites studied with increasing temperature may be attributed to the increased activity of the pyramidal (**c** + **a**) slip mode. It is clear that the softening processes depend strongly on the testing temperature. The glide of the **(c + a)** dislocation depends on the testing temperature, applied stress and the microstructure (the density of basal and pyramidal dislocations). At lower temperatures, grain boundaries and twins act as obstacles to the dislocation motion.

5. Conclusions

The work hardening behaviour of a ZC63/10SiC composite was investigated at several temperatures between room temperature and 200 ºC at an initial strain rate of $8.3\text{x}10^{-3}\ s^{-1}$. A significant role of the testing temperature on the deformation behaviour of the composite was revealed clearly. The flow stress decreases with increasing temperature. The work hardening rate becomes very close to zero at higher temperatures. The shape of the true stress-true strain curves at higher temperatures indicates a significant softening mechanism. The deformation behaviour of the composite can be attributed to the activity of the second-order pyramidal slip systems. The dislocation glide on the second-order pyramidal planes and double cross slip of (**c** + **a**) screw dislocations have a significant effect on the work hardening of the composite, especially at elevated temperatures.

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