Tensile behaviour of squeeze cast AM100 magnesium alloy and its Al₂O₃ fibre reinforced composites

S. Jayalakshmi, S.V. Kailas, S. Seshan*

Department of Mechanical Engineering, Indian Institute of Science, Bangalore 560 012, India

Received 22 November 2001; accepted 22 April 2002

Abstract

Magnesium alloys are increasingly used in automotive and aerospace applications mainly due to their light weight combined with reasonably high tensile properties. In addition to providing a large reduction in weight, magnesium alloys exhibit excellent machinability and good damping capacity. However, their low mechanical properties when exposed to elevated temperatures limit their usage. Making composites out of these magnesium alloys by reinforcing them with ceramic particles or fibres appears to be a viable alternative for improving their thermal stability. The work reported here involved experimental studies on the tensile behaviour of AM100 magnesium alloy and its composites at different temperatures. Fractographic studies justify the effect of temperature on the tensile behaviour.

Keywords: Magnesium alloys; A. Metal matrix composites (MMCs); B. Mechanical properties; D. Fractography

1. Introduction

In recent times, magnesium alloys have gained a prominent position in automotive, aerospace and electronic industries where weight reduction is an important requirement. Magnesium alloys offer light weight, high stiffness, excellent machinability, good dimensional stability and damping capacity [1]. Among the currently used magnesium alloys, the Mg–Al systems (with and without zinc) offer reasonably high strength properties at room temperature and are in wide use. Though other alloy systems such as those containing zirconium, rare earth elements and thorium exhibit slower drop in properties up to 250 °C, their high cost and difficulties in casting have limited their use to certain specific applications. The Mg–Al system accounts for about 90% of the total applications involving magnesium alloys and find usage in computer housings, portable telecommunication instruments, passenger seat frames and instrument panels [2]. However, Mg–Al alloys can be used safely only up to about 150 °C; even at this temperature, considerable loss in strength is evident [3]. Hence, it is obvious that their application as structural materials is restricted due to the reduction in their mechanical properties at increasing temperatures. Therefore, a need has been felt to improve the mechanical properties of these alloys at high temperatures.

Literature review [4–7] indicates that making composites out of the alloys would provide a workable solution to the above. The base magnesium alloys (matrix) may be reinforced with ceramic constituents (in the form of particles, fibres or whiskers) that would provide improvement in strength properties at high temperatures. Earlier investigations [8–11] on the composites of aluminium and copper alloys point out that in addition to improvement in strength and thermal stability, appreciable enhancement in hardness, stiffness and wear resistance was also realized.

The squeeze casting process (that refines grains and eliminates porosity) is suitable to produce premium quality castings. An extension of the above, the squeeze infiltration method, is a simple and economical method for producing short fibre reinforced metal matrix composites [10,12,13]. Literature available on magnesium alloy castings and their composites produced using the squeeze casting technique is rather limited.

In this work, magnesium alloy AM100 and its composites (reinforced with saffil alumina short fibres) were processed through the squeeze casting technique. The alloy and composite castings produced were characterized for their tensile behaviour at different temperatures and the fractured specimens were examined using a scanning electron microscope.

* Corresponding author. Fax: +91-80-3600648.
E-mail address: seshan@mecheng.iisc.ernet.in (S. Seshan).
2. Experimental details

The magnesium alloy AM100 (Mg–9.3 to 10.7Al–0.13Mn) castings and composites were produced using the squeeze casting and squeeze infiltration techniques, respectively. The squeeze pressure was maintained at 40 MPa for both the alloy and its composites. Saffil alumina short fibres were used as the reinforcement material (fibre length: 200 μm and mean fibre diameter: 3 μm). Three volume fractions (viz. 15, 20 and 25%, respectively), of fibre preforms were used. The cylindrical preforms were of diameter 70 mm and height 30 mm and the initial preform temperature was 850 °C. The base alloy castings and the composites produced were heat-treated to the T6 condition for attaining peak hardness. For microstructural studies, specimen preparation included initial dry polishing on SiC abrasive sheets (220, 320, 400 and 600 grits) followed by wet alumina and diamond polishing. The polished specimens were etched in a glycol etchant for 30–60 s. Tensile tests of the peak hardened test specimens were conducted in a 2-ton Monsanto tensometer (with a high temperature furnace attachment) at a controlled strain rate of 0.001 s⁻¹. Tensile tests were conducted at four different test temperatures, viz. 25 (room temperature), 100, 150 and 200 °C, respectively. Fracture analysis was done using a Jeol scanning electron microscope.

3. Results and discussions

3.1. Microstructure

Typical microstructures of the unreinforced alloy and its composites (20% V_f) are shown in Figs. 1 and 2, respectively. Microstructural analysis of the unreinforced alloy (Fig. 1) indicates the presence of eutectic along the grain boundaries, within which is present the β-Mg₁₇Al₁₂ precipitates [2,14–18]. The precipitates are hard and brittle [2] and contribute to the high hardness values. Fig. 2 shows the cross-section of the composite cut in a direction normal to the thickness direction of the preform. The short fibres are distributed in a planar, isotropic orientation as a result of the method of production of the preform [15,19]. In the composites, the fibres are uniformly distributed throughout the matrix. Earlier works [20,21] indicate that the fibre/matrix interface acts as nucleation sites for precipitation to occur during aging, thereby increasing the hardness with increasing fibre volume fraction. It is observed that the highest volume fraction (25%) resulted in a hardness value (165 BHN) that is nearly twice that of the unreinforced base alloy (85 BHN). In an earlier work reported elsewhere [22] it was observed that the aging behaviour of AM100 magnesium alloys and its composites exhibited a rapid reduction in aging time with increase in aging temperature, indicating the acceleration in the aging kinetics. Such a behaviour has also been observed earlier in aluminium composites [23,24].

3.2. Tensile behaviour

3.2.1. Unreinforced alloy

The ultimate tensile strength of the unreinforced base alloy at different test temperature is shown in Fig. 3. The unreinforced alloy is very sensitive to temperature and undergoes a drastic reduction in strength as the test temperature increases. At the highest test temperature of 200 °C, the strength drops to almost one-third of its room temperature value. Fig. 4 shows the variation of % elongation with test temperature. It is observed that the % elongation of the alloy increases initially with increasing test temperature; it reaches a maximum value at 150 °C and reduces there after. The highest test temperature (200 °C) being very close to the aging temperature (225 °C), gross precipitation coarsening would occur leading to a reduction in strength as well as ductility of the alloy [24].

The fractographic evidences of the alloy specimens are shown in Fig. 5. Fig. 5(a) shows dominant brittle intergranular fracture at room temperature. The presence of brittle Mg₁₇Al₁₂ precipitates along the grain boundaries contributes to this. As the temperature increases, flow of the
material would introduce ductility into the alloy with the fracture surface showing large dimples. This change in the fracture mode may be due to the introduction of additional slip planes [25] in the alloy that occurs with increasing temperature. At 150 °C, the alloy thus shows prominent ductile failure (Fig. 5(b)) that is in consensus with the high elongation values obtained. But, at 200 °C, the highest test temperature, the fracture behaviour changes and the alloy again fails by intergranular failure (Fig. 5(c)) indicating the weakening of the grain boundaries due to precipitate coarsening [2].

3.2.2. Composites

Fig. 3 shows the variation of tensile strength of the composites (of different volume fractions) with temperature. At room temperature, composites of all volume fractions exhibit similar behaviour as the base alloy, indicating that the room temperature behaviour is largely controlled by the inherent brittle matrix. However, with increase in temperature, unlike the base alloy, the composites do not exhibit any monotonic decrease in strength. This is attributed to the load bearing capacity of the fibres at higher temperatures. Fig. 4 shows the variation of % elongation of the composites with temperature. The composites exhibit lower ductility in comparison to the base alloy, the reason being the presence of brittle ceramic fibres. Therefore, with increase in fibre volume fraction, the % elongation of the composites continues to decrease. As the temperature increases, the difference in the elongation values amongst the MMCs reduces such that at the highest test temperature, all the composites exhibit almost the same
values of % elongation. In comparison, the base alloy exhibits elongation values that are almost an order of magnitude greater than that of the composites, indicating the influence of fibres on the mechanical behaviour.

Fig. 6(a)–(d) show the representative scanning electron micrographs of the fractured surfaces of the composites (20% $V_f$) tested at different temperatures. At room temperature, MMCs with all volume fractions exhibit similar behaviour as that of the base alloy. Fig. 6(a) provides the evidence of large matrix cracking depicting that the inherently brittle matrix material largely controls the room temperature behaviour of the composites. The absence of plastically induced load transfer to fibres, due to the limited ductility of the matrix causes the early failure of the matrix. The few fibre pull-outs seen in Fig. 6(a) further indicate that the interfacial strength of the composite is good [24]. As the temperature increases to 100°C, the load is taken up by the fibres due to the plastic flow of the matrix, thus increasing the absolute value of UTS at elevated temperatures. Fig. 6(b) shows the reduction in matrix cracking and an increase in the flow of the matrix, as seen from the dimples on the fracture surface. At this temperature, fibre pull-outs are also observed. At 150°C, overaging of precipitates occur [22,24], in addition to the large flow of matrix that leads to fibre cracking. As the precipitates are largely present along the fibre/matrix interface [15,21], the interface is weakened resulting in large fibre pull-outs (Fig. 6(c)). In these randomly oriented fibre composites, fibre/matrix debonding and fibre failure occur in fibres that are oriented normal to the loading direction, whereas fibre pull-outs are dominant in fibres that are aligned along the loading direction. Such occurrences have been earlier observed by many investigators [5,24,26,27]. From Fig. 6(c), it can be seen that fibre pull-outs largely occur in the fibres that are oriented parallel to the loading direction. With increase in test temperature (200°C), overaging process accelerates leading to further reduction in the strength of the composites. Earlier works [22,24] also indicate that higher the fibre volume fraction and aging temperature shorter is the attainment of peak aging time. Hence, higher volume fraction composite overages more rapidly than its lower volume fraction counterparts. The reversal in trend observed in the strength values of the composites at higher temperatures (Fig. 3) is attributed to this rapid overaging process. In addition to overaging, the softening of the matrix at these temperatures transfers large load to the fibres resulting in fibre cracking (Fig. 6(d)). Chawla [28] suggests that the flow of the matrix that occurs at high temperatures causes large local stresses on the fibres resulting in fibre deformations and fibre breakage. Any flow of the matrix surrounding the fibre would result in a highly directional, local stress field on the fibre. As the temperature increases, this stress increases and such a high local stress would cause local plastic deformation. When the fibre that is carrying this high stress reaches its fracture strain, it would crack resulting in complete failure, as seen in Fig. 7.
4. The strength reduction is mainly caused by overaging when compared to that of the unreinforced alloy. Though strength reduction with temperature occurs in the composites, they still exhibit reasonably high values for many applications.

4. Conclusions

1. The inherent brittle nature of AM100 alloy, determined by the nature and distribution of precipitates, dominates its tensile behaviour at all test temperatures.
2. The room temperature strength of the composite is dominated by the brittle alloy matrix. At higher temperatures, the strength is attributed to the load carrying capacity of the fibres.
3. The composites exhibit high thermal stability when compared to that of the unreinforced alloy. Though strength reduction with temperature occurs in the composites, they still exhibit reasonably high values for many applications.
4. The strength reduction is mainly caused by overaging and softening of the matrix alloy. This indicates that in addition to matrix flow properties due consideration should be given to the influence of fibres on the precipitation.

References

[26] Liu X, Bathias C. Defects in squeeze-cast Al2O3/Al alloy composites
and their effects on mechanical properties. Compos Sci Technol 1993; 245–52.