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Tensile strength and fracture toughness of two magnesium metal matrix composites

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Metal matrix composites of two magnesium alloys (AM100 and ZC63) with saffil alumina fibre reinforcements were produced using a squeeze infiltration technique. Mechanical properties were assessed, followed by analysis of the fractured specimens. From the strength, toughness and the fractographic analysis, attempts were made to elucidate the influence of the matrix, fibre volume fraction and the fibre/matrix interface on the properties.

Key words: Magnesium metal matrix composites, Tensile strength, Toughness, Fractography.

Introduction

Metal matrix composites (MMCs) are superior to base alloys because of their ability to achieve improved specific mechanical properties such as stiffness, hardness, ultimate tensile strength, wear resistance and creep [1, 2]. However, coupled with these improvements is an unavoidable reduction in fracture-related properties such as ductility and fracture toughness, which generally limit the application of these materials. In recent times, magnesium alloys and their composites have attracted considerable attention for high performance applications in automotive industries [3]. However, unlike Al-MMCs, only very few studies have been focused on Mg-MMCs [3]. In our earlier studies of Mg-MMCs, we have reported [4-6] significant improvements in hardness, elastic modulus, elevated temperature strength and wear resistance of the composites. In the work reported here, saffil alumina short fibre reinforced Mg-MMCs were characterized for room temperature strength and fracture toughness. This investigation therefore provides some useful and relevant information on the response of two Mg-based composites to tensile and impact loading conditions.

Experimental Details

Two commercial magnesium alloys AM100 (Mg-9.3 to 10.7Al-0.13Mn, composition in wt.%) and ZC63 (Mg-5.5 to 6.5Zn-2.5 to 3.5Cu-0.25 to 0.75Mn, composition in wt.%) were selected as matrix materials. The alloys were reinforced with saffil alumina short fibers (cylindrical preforms of dia: 70 mm and ht: 35 mm; and of V_f: 15%, 20% and 25%, respectively), using a squeeze infiltration technique at a pre-selected pressure of 40 MPa. The unreinforced base alloys and their composites were heat-treated to T6 condition (detailed information on microstructure and aging response are given elsewhere [4, 5]) and tested for tensile properties at a controlled strain rate of 0.001/s. Instrumented charpy tests were carried out on unnotched bars of dimensions $10\times10\times55$ mm^3 and on notched bars with a notch tip radius of 0.02 mm. Tests were repeated five times for tensile tests and three tests were conducted for the impact loading condition. The fracture surfaces were examined using a scanning electron microscope (SEM).

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Results and Discussion

Tensile Strength

The room temperature ultimate tensile strength (UTS) and yield strength (YS) shown in Fig. 1a indicates that the addition of fibers does not provide significant improvements in strength in both the AM100 and ZC63 systems. This is mainly due to the residual tensile stresses present in the matrix, which arise due to the thermal mismatch between the fiber and the matrix [4, 5]. These stresses, in combination with the applied tensile stress, promote easy failure of the composites [5]. In both the composites, 15%V_f gives no change in strength (in AM100) or a lower strength (in ZC63) when compared to the unreinforced base alloys. It can also be observed that for $V_f \geq 20\%$, the behavior of the two composites are similar, which indicates that the properties of the fibre dominate in defining the behavior.

It is also seen that due to the presence of brittle precipitates along the grain boundaries [4], the AM100 alloy was brittle, as observed from the low value of

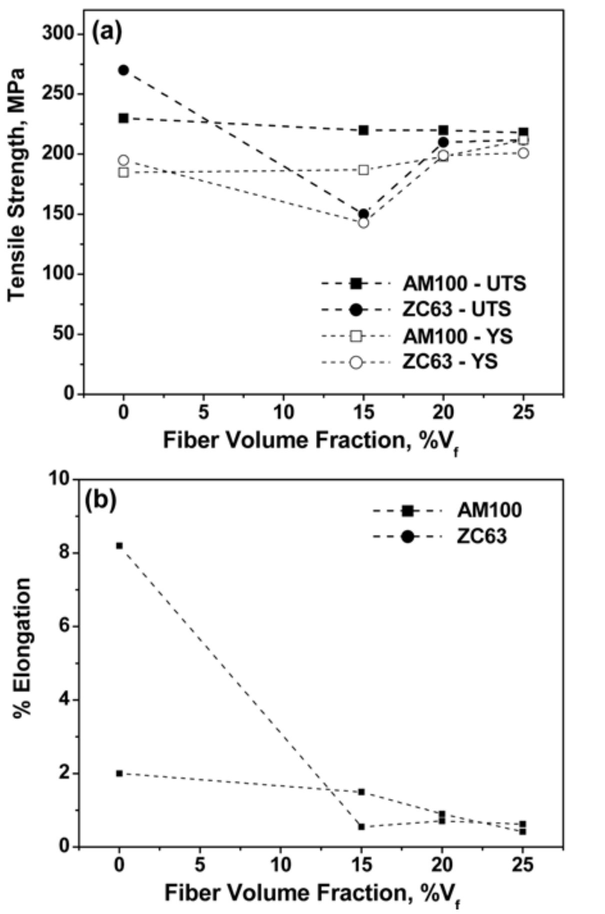

Fig. 1. Variation of (a) tensile strength and (b) %elongation of AM100 and ZC63 systems.

elongation at fracture, shown in Fig. 1b. Hence the unreinforced alloy fails by intergranular failure (Fig. 2a). In the AM100 composites (Fig. 2b), failure occurs by cracking of the brittle matrix because, plastically-induced load transfer to the fiber does not occur due to the presence of brittle precipitates along the grain boundaries and at the fiber/matrix interface [4].

In the ZC63 alloy, a ductile failure was observed (Fig. 2c), as indicated by the large value of elongation. In the ZC63 composites, the lower strength of the composites (especially at 15%V_f) was attributed not only to the residual stresses but also to the fiber volume fraction. Friend [7] observed that a critical volume fraction, V_{crit}, should be exceeded in order to achieve a significant strength improvement. The value of V_{crit} depends largely on the matrix properties such as the ultimate tensile strength and yield strength, and especially on the difference between them (rate of work-hardening), which would affect the plastically-induced load transfer to the fibers [7]. Hence composites with $V_f < V_{crit}$ would exhibit a much lower strength than that of unreinforced alloy. For the ZC63 matrix, the calculated values of V_{crit} that is required to provide enhancement in strength properties is 16%V_f [5]. Hence for composites with $V_f \leq 16\%$, fracture occurs at low strength and results in catastrophic fiber failure (Fig. 2d). Indeed, in the composites, in particular, those with $V_f < V_{crit}$, the fibers reach their breaking strain [5], resulting in lower ductility of ZC63 composites (15% V_f) when compared to 15% V_f AM100 composites, for which $V_{crit} \sim 10\%$ [5]. It is hence evident that the inher-

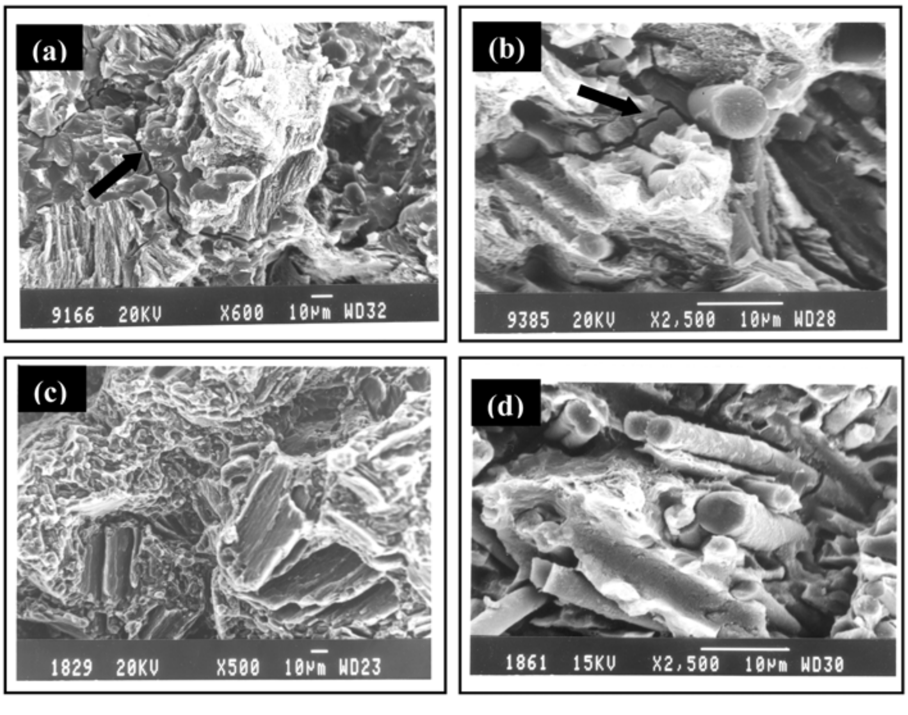

Fig. 2. Fractographic evidence after tensile tests showing (a) intergranular failure (arrow) in AM100 alloy (b) matrix cracking (arrow) in AM100 composite (c) ductile failure in ZC63 alloy and (d) fiber failure in ZC63 composite.

ent matrix properties play a major role in determining the tensile behavior of the composites.

Impact Strength and Fracture Toughness

The impact strength of the two unreinforced alloys and their composites are shown in Fig. 3a. The relatively higher energy absorbed by the ZC63 system is indicative of the inherent ductility of the ZC63 matrix that resists the propagation of cracks, and results in a relatively higher impact strength. The impact energy of both the composites is significantly lower than that of the unreinforced matrix. The small strain to failure and the high stiffness of the fibers restrict the plastic deformation of the matrix, thereby resulting in a low impact energy. It is also observed that the presence of the notch drastically reduces the impact energy; this is attributed to the stress concentration present at the tip of the notch [8, 9].

As shown in Fig. 3b, under both the un-notched and notched conditions, ZC63 alloys and composites exhibit higher fracture toughness than the AM100 system. This is attributed to the inherent ductility of the ZC63 matrix that facilitates plastic deformation prior to failure, thereby offering resistance to crack propagation. In contrast, the AM100 alloy exhibits brittle intergranular failure with features characteristic of cleavage morphology (Fig 4a). Earlier work on AZ91/saffil alumina short fibre composites by Purazrang et al. [3] also showed such cleavage morphology, which was attributed to the poor accommodation of micro-plasticity by the alloy. In the present study, the restricted plastic deformation of AM100 is attributed to the presence of brittle $Mg_{17}Al_{12}$ precipitates at the grain boundaries [4]. However, the fracture surface of ZC63 alloy shows ductile failure indicating the occurrence of plastic deformation before failure (Fig. 4b). It can be observed that the addition of fibers causes a large decrease in the toughness for both the alloy systems (Fig. 3b). It can also be observed from Fig. 3b that the presence of a notch drastically reduces the toughness values of the composites. As suggested by Lim et al. [8], cracks initiate at areas of high dislocation density (at the fiber/matrix interface) and the propagation of such cracks would occur along the regions where the stress concentration is high. Hence, when a composite containing a defect or crack is subjected to loading, there would exist a highly strained region at the crack tip where different failure mechanisms would operate [9]. It was suggested that when such a crack propagates through the matrix containing fibers, the following mechanisms

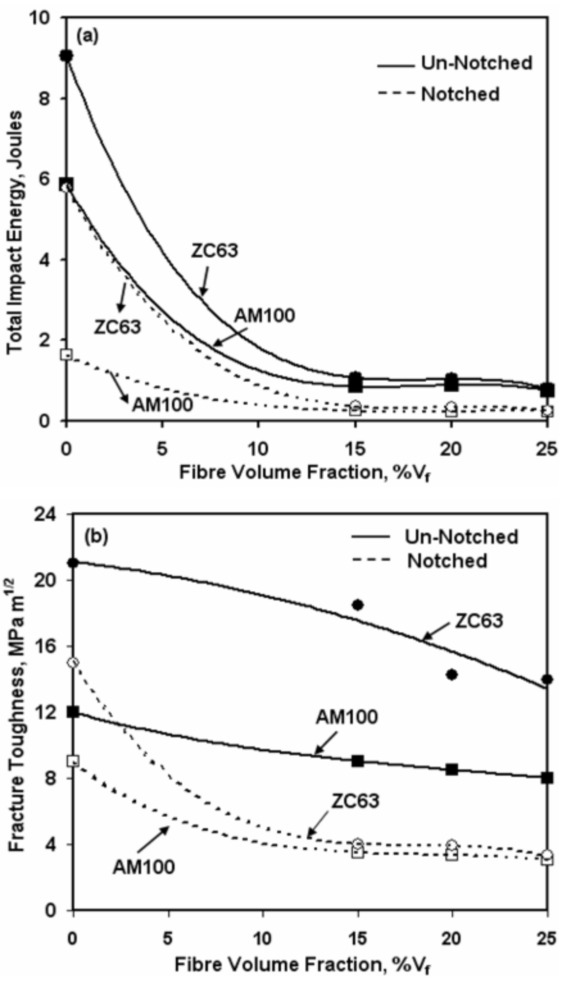

Fig. 3. Variation of (a) impact strength and (b) fracture toughness, with fibre volume fraction of AM100 and ZC63 alloy systems.

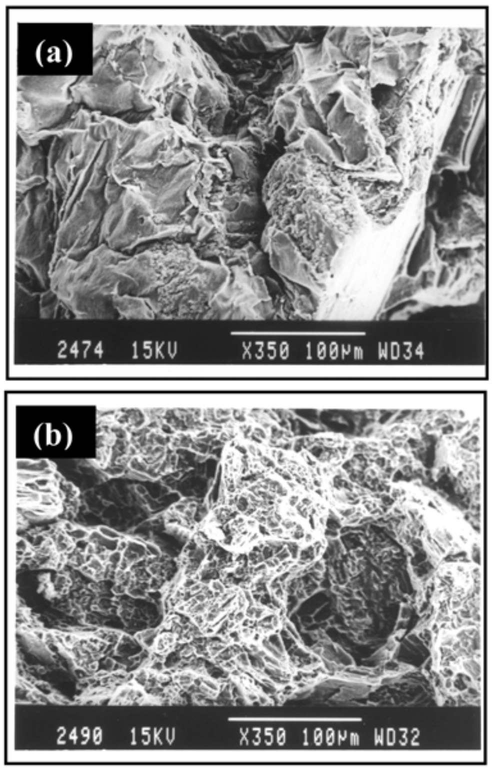

Fig. 4. Fracture surfaces of un-notched samples showing (a) cleavage fracture in AM100 alloy and (b) dominant ductile failure in ZC63 alloy.

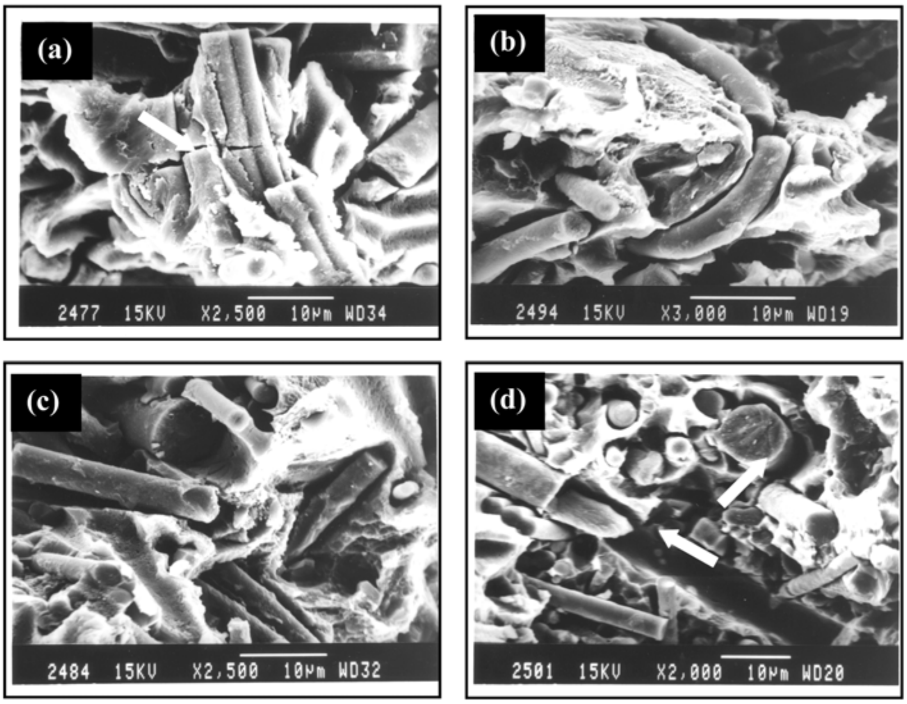

Fig. 5. Fractography of impact tested specimens (a) representative fracture surface of an un-notched composite (AM100) shows easy crack propagation through fibers (arrow) (b) 15%V_f ZC63 un-notched composite indicating dominance of matrix ductility (c) notched 25%V_f AM100 composite showing fiber fracture along the impact plane and (d) notched 25%V_f ZC63 composite showing chopping (arrow) and splitting of fibers leading to catastrophic failure.

may be present: matrix fracture, fibre/matrix debonding, fibre fracture and fibre pull-out. In conjunction with these mechanisms, fibre bridging and crack deflection would also take place. However, the extent to which these mechanisms occur in a given system would depend on the fibre/matrix interface of the system [9]. Dellis et al. [10] reported that the reduced toughness in Zn-Al matrix composites was due to the occurrence of damage in the form of fibre cracking and interfacial debonding. Harris [11] suggested that a sequence of these events would lead to easy propagation of cracks.

In the present study, the fractographic evidence indicates that a combination of such mechanisms occurs in the composites of both the alloys. In the un-notched condition, crack propagation occurs through multiple fibers in AM100 composites, whereas in a ZC63 composite of higher volume fraction chopping of fibers takes place. A representative fractograph of an un-notched AM100 sample is shown in Fig. 5a. Both the composites exhibit good interfacial bonding, with very little de-cohesion and fibre pull-outs. Though the over all trend of impact strength and fracture toughness for both the alloys and composites is downward, i.e., the properties decrease with an increase in volume fraction of fibres, it may be noted that the 15%V_f ZC63 composite shows a relatively higher value of fracture toughness. This is probably due to the weak effect of fibers, resulting in the predominance of the matrix properties. The dominance of the matrix ductility of the 15%V_f ZC63 composite is shown in Fig. 5b. However, the contribution of such plastic deformation is limited in a Charpy test, as the high strain rate and the constraint of the matrix favor a brittle failure of the composite [10]. Hence, in the notched condition, the fibers appear to have broken along the impact plane (Fig. 5c). Such failures along the plane of rupture resulting in large fibre breakage were reported earlier by Kehoe and Chadwick in Zn-Al composites [12]. Fibre debonding, large fibre chopping and fibre fracture are observed along the impact plane for the ZC63 composite, highlighting the influence of the notch (Fig. 5d).

Conclusions

The properties of the two Mg-MMCs investigated are largely dependent upon the fibre, matrix and the fibre/ matrix interface. In a composite with a brittle matrix such as AM100, though the interfacial bond is strong and tensile strength is not significantly affected by the volume fraction of the reinforcement, impact loading leads to a more brittle and catastrophic failure even in the un-notched condition, wherein cracks propagate right through the fibre and matrix material. In a composite with a ductile matrix such as ZC63, though the bond strength is good, the tensile strength was found to be dependent on the fiber volume fraction. However, under impact loading conditions, the higher fracture toughness of the ZC63 is due to the higher ductility of the ZC63 matrix, which resists easy crack propagation. Also, choosing a proper volume fraction of fibers is critical, particularly in a ductile matrix such as ZC63, wherein the matrix properties determine the material response. Hence, in terms of strength, the AM100 matrix might be preferable, while in terms of fracture toughness the ZC63 matrix provides better resistance. Therefore, the base Mg alloy matrix should be properly selected depending on the end application and the property requirement.

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