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The sliding wear behavior of TiC_p/AZ91 magnesium matrix composites

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Abstract The AZ91 metal matrix composites (MMCs) reinforced with 5, 10 and 15 wt.% TiC particulates are fabricated by TiC_p–Al master alloy process combined with mechanical stirring. The effects of TiC particulate content, applied load and wearing time on the sliding wear behaviors of the composites were investigated using MM-200 wear testing apparatus. The results show that the wear resistance and friction coefficient of the composites increased and decreased with increase of the TiC particulate content, respectively. The wear volume loss and friction coefficient of the reinforced composites as well as the unreinforced AZ91 matrix alloy increased with increase of applied load or wearing time, but the increase rates of the reinforced composites in two performance is lower than those of the unreinforced AZ91 matrix alloy. Furthermore, the sliding wear behavior of the composites and the unreinforced AZ91 matrix alloy is characterized by ploughing, adhesion and oxidation abrasion.

Introduction

Metal matrix composites have been receiving widespread attention in recent years due to their promising advanced properties. Among numerous MMC systems under various stages of development, aluminum and magnesium based MMCs are of great interest to the automotive and aerospace industries because of their low density and superior specific properties [1–4]. The mechanical and tribological behaviors of the Al-based MMCs have been studied extensively and the composites exhibit better wear resistance than the unreinforced matrix alloys for sliding against metals and abrasives [3, 4]. Moreover, wear-resistant ceramic-reinforced Al MMCs have also been used in tribological applications such as brake rotors, piston rings and cylinder liners in automobiles [4]. It is well known that magnesium is the lightest metallic structural material with a density two-thirds that of aluminum. Therefore, the particulate reinforced magnesium matrix composite with high specific strength and stiffness, good damping capacities, dimensional stability and creep resistance would provide attractive alternatives to Al MMCs in the future [1, 2, 5–9]. Despite the potential of Mg based MMCs, the study on them has been relatively limited as compared with the abundance of Al MMC investigations over the last two decades, and research on the tribological properties of these materials is even scarcer [7]. Less information concerning tribological behavior of Mg-based MMCs reveals that tribological properties of Mg alloys can be significantly improved by the addition of hard ceramic fiber or particulate reinforcement [7, 10–14]. Lim et al. [7] studied wear behavior of SiC_p-reinforced magnesium MMCs and abrasion, oxidation, delamination, adhesion, thermal softening and melting were identified as the operating wear mechanisms at varying loads of 10 and 30 N with sliding velocity of 0.2–5.0 m/s. An important point in this investigation is that the wear

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rate initially decreased and then slightly increased with sliding speed. Alahelisten et al. [10] investigated sliding, abrasion and erosion behavior of alumina fibre reinforced Mg and Mg–9Al–Zn matrix composites. They concluded that an increase in the wear resistance can be obtained with an increase in volume fraction of fiber, and the wear resistance increased in two-body abrasion, whereas it decreased in three-body abrasion and erosion. Saravanan and Surappa [11] investigated wear resistance of Mg-30 vol.% SiC_p composites during adhesive wear, and reported the wear resistance was improved, as compared to base Mg. Sharma et al. [12] evaluated sliding wear behavior of feldspar particle-reinforced magnesium alloy composites. The wear rate reduced with increasing feldspar content. Thakur and Dhindaw [13] investigated the influence of interfacial characteristics between SiC_p and Mg/Al metal matrix on wear, coefficient of friction. It was indicated that the interparticle distance of SiC particles influences the tribological properties of composites. Lim et al. [14] investigated wear of magnesium composites reinforced with nano-sized alumina particulates. They pointed out that the wear resistance of the composites was improved with increasing amounts of reinforcement, and identified that the abrasion, adhesion and thermal softening were dominant wear mechanisms while wear mechanism by delamination was not evident.

Best to our knowledge, no information is available in literature concerning the tribological properties of TiC particulates reinforced Mg MMCs, especially the sliding wear. In this study, TiC_p/AZ91 composites containing the different TiC particulate content were fabricated by TiC_p-Al master alloy process combined with mechanical stirring [8]. The primary aim of this study is to investigate the sliding wear behavior of TiC_p/AZ91 magnesium alloy composites in dry sliding. Furthermore, the microstructures, hardness, wear debris and morphologies of worn surface of the composites are also discussed. Experiments with the unreinforced matrix alloy are also presented for comparison. It is anticipated that the preliminary results can be significant in promoting the development of the research and application of TiC particulate reinforced magnesium matrix composites to industrial production.

Experimental

The TiC_p/AZ91 magnesium composites containing the different TiC particulate content (matrix composition corresponding Mg-9pct Al-1 pct Zn of AZ91) used in this study was fabricated by adding a TiC–Al master alloy processed via self-propagating high temperature synthesis (SHS) reaction in Al–Ti–C system into molten magnesium and using the mechanical stir casting technique [8, 9]. Starting materials producing TiC–Al master alloy are pure titanium powder (99.5%, ~25 μm), aluminum powder (98.4%, ~29 μm) and carbon powder (99.9%, ~38 μm) in this work. The TiC–Al master alloy containing TiC_p particulates with a size of ~5 μm as reinforcement was processed via the SHS reaction of Ti–C–Al system in a vacuum electrical resistance furnace. Moreover, 500 g of pure magnesium was melted at 750 °C in a graphite crucible in electric resistance furnace under SF_6/CO_2 protective atmosphere, and the desired amounts of the master alloy, Al and Zn were then introduced into the magnesium melt, held at that temperature until they were dissolved. After dissolving, the melt was stirred with a graphite stirrer for about 30 min and then, poured into a steel mould to obtain the TiC_p/AZ91 magnesium composites.

Friction and wear tests were conducted in air at room temperature in a block-on-ring machine. The block was loaded against the ring by a dead weight loading system. The unreinforced AZ91 matrix alloy and TiC_p/AZ91 composites were used as the block with the size of $10 \times 10 \times 14$ mm^3. The counterpart ring, 40 mm in outside diameter and 10 mm in thickness, is made of GCr15 bearing steel with a bulk hardness of HRC62 ± 2. Tests were carried out at fixed sliding velocity of 0.419 m/s, load of 9.8, 29.4, 58.8 and 88.2 N, and wearing time of 10, 20, 30 and 40 min (corresponding the sliding distance of 251, 502, 753, and 1004 m), respectively. Prior to wear testing, the surface of the specimens were polished under water using silicon carbide papers from 180 to 1000 mesh, and the counterpart ring was trimmed by a grinder attached to the wear test machine, so that a linear contact between the steel ring and the specimen was obtained. After this, the samples and rings were washed in acetone to ensure that the tests were carried out under nominally dry sliding condition. All weight loss data of the block specimen, weighed by a photoelectric balance with the accuracy of ±0.1 mg, were converted to volume loss using the measured densities. Friction coefficient was calculated from the volume loss and the moment of the force measured by the test machine during experiment, respectively.

The microstructures, worn surfaces and wear debris of the unreinforced AZ91 matrix alloy and TiC_p/AZ91 composites were examined and analyzed using scanning electron microscopy (SEM) (Model JSM-5310, Japan) equipped with energy-dispersive spectrum

(EDS) (Model Link-Isis, Britain) and X-ray diffraction (XRD) (Model D/Max 2500PC Rigaku, Japan), respectively.

Results and discussion

Microstructures of the composites

Figure 1a and b show the typical SEM micrographs of AZ91 alloy and 10 wt.% TiC_p/AZ91 magnesium composites, respectively. It can be seen that TiC particulates in the composites are fine (~5 μm) and spherical, and the distribution of TiC particulates is relatively homogeneous throughout the AZ91 matrix. Furthermore, the microstructures of the composites all reveal the finer grain than that of the AZ91 alloy. The grain refinement of the composites may be caused by the effect of pinning of TiC particulates.

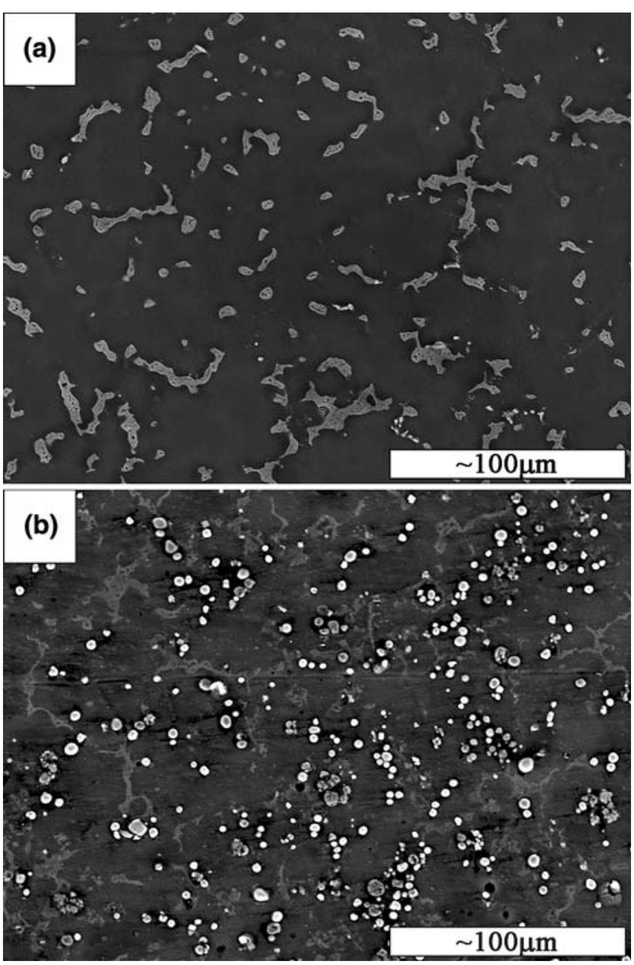

Fig. 1 Microstructures of (**a**) AZ91 alloy and (**b**) 10 wt.% TiC_p/AZ91 magnesium composite

The hardness values (HB) of AZ91 alloy, 5, 10 and 15 wt.% TiC_p/AZ91 designed composites are 58, 70, 74 and 81, respectively. Apparently, the hardness of the composites is higher than that of AZ91 alloy and the hardness values of the composites increase with the increase of TiC content. Increase of the composites hardness can be attributed primarily to: (a) the presence of relatively harder ceramic particulates in the matrix, (b) TiC particulates to refine the microstructures of the composites, and (c) a higher constraint to the localized matrix deformation during indentation due to their presence. These results are consistent with the similar findings obtained on Mg and Al based composites [15–17].

The sliding wear behavior of the composites

Figure 2a and b shows the variation of volume loss and friction coefficient of the TiC_p/AZ91 composites with

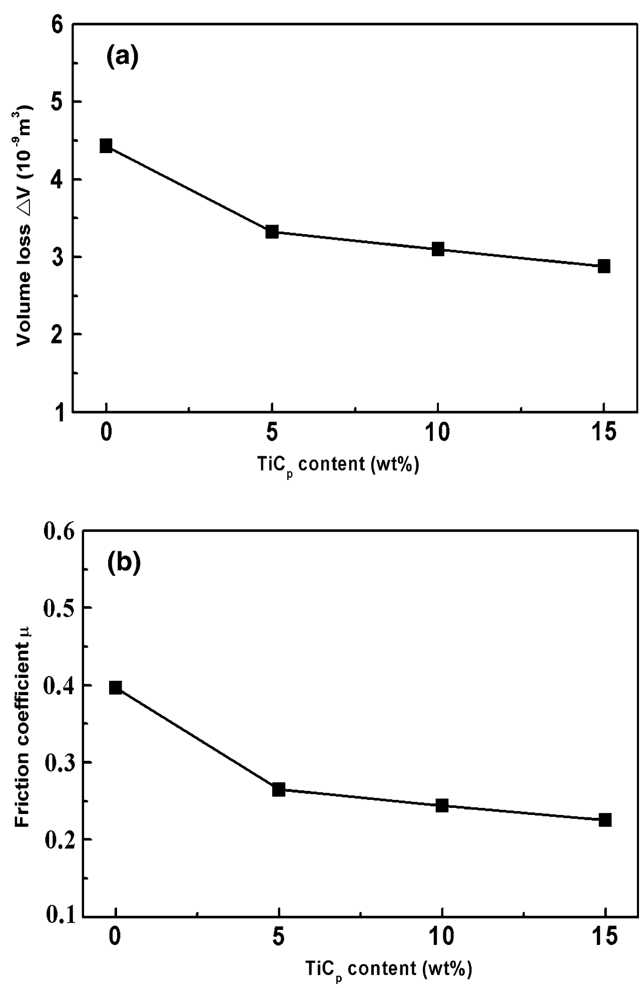

Fig. 2 The variation of (**a**) volume loss and (**b**) friction coefficient of TiC_p/AZ91 composites with TiC particulate content

TiC particulate content under a load of 29.4 N, a wearing time of 20 min and a sliding velocity of 0.419 m s^{-1}, respectively. It is obvious that volume loss and friction coefficient of the composites decrease with increase in TiC particulate content. Furthermore, volume loss and friction coefficient of the composites decrease by 65% and 56%, respectively, when TiC particulate content increases from 0 to 15 wt.%. It is well known that the wear resistance is defined as the inverse of volume loss [18]. Therefore, the wear resistance of the composites increases with increase in TiC particulate content, and this can be primarily attributed to as follows: (a) increasing in hardness of the composites with the increase of TiC content, (b) decreasing of the contact area between the matrix of the composite and counterpart ring due to the addition of the TiC particulates, and (c) increasing ability to bear loads, strengthen matrix and prevent plastic deformation of TiC particulates with the increase of TiC content.

According to literature [19], the TiC particulates in the TiC_p/AZ91 composites change contact property, reduce contact area and decrease adhesion trend between the matrix and counterpart ring. Therefore, the decrease of friction coefficient of the composites with the increase of TiC particulate content may result from the decreasing adhesion trend between the matrix and counterpart ring. Additionally, TiC particulates in the composites are spherical, fine and in situ formed, and the surface of TiC particulates is uncontaminated [8]. Therefore, strong interface bonding between TiC particulate and matrix can prevent the particulate desquamating from the matrix and reduce the tendency of the abrasive wear. This help to decrease the friction coefficient of the composites too.

Figure 3a and b show the variation of volume loss and friction coefficient of the unreinforced AZ91 alloy and the TiC_p/AZ91 composites with the applied loads under a wearing time of 20 min and a sliding velocity of 0.419 m s^{-1}, respectively. Apparently, it can be seen from Fig. 3a that both the volume loss of AZ91 alloy and TiC_p/AZ91 composites increase with increase of the load. The increase of the load can enhance plastic flow and transfer of metal in friction surface, and so the volume loss of two kinds of material increases. It can also be seen that the wear resistance of the composites is obviously better than that of AZ91 alloy. Furthermore, the increase rate of the volume loss of AZ91 alloy is obviously higher than those of TiC_p/AZ91 composites. It is well known that hard particulates in composites can act as hard barrier to support action and resist plastic deformation during friction and wear. This may lead to lower increase rates of the volume loss of the composites as comparison with the AZ91 alloy.

Both the friction coefficient of AZ91 alloy and TiC_p/AZ91 composites increases with increase of the load, as shown in Fig. 3b. The contact surface between wear specimen and counterpart ring during sliding wear is usually in an elastoplastic state, and the true contact area and the surface roughness increase with increase of the applied load. Therefore, the increase of the surface roughness maybe leads to increase of the friction coefficient with increase of the load. Moreover, the increase rate of the friction coefficient of the AZ91 alloy is higher than that of the composites. The resisting adhesion trend of TiC particulates can result in lower increase rate of the friction coefficient of the TiC_p/AZ91 composites.

Figure 4a and b show the variation of volume loss and friction coefficient of AZ91 alloy and the TiC_p/AZ91 composites with wearing time under a load of

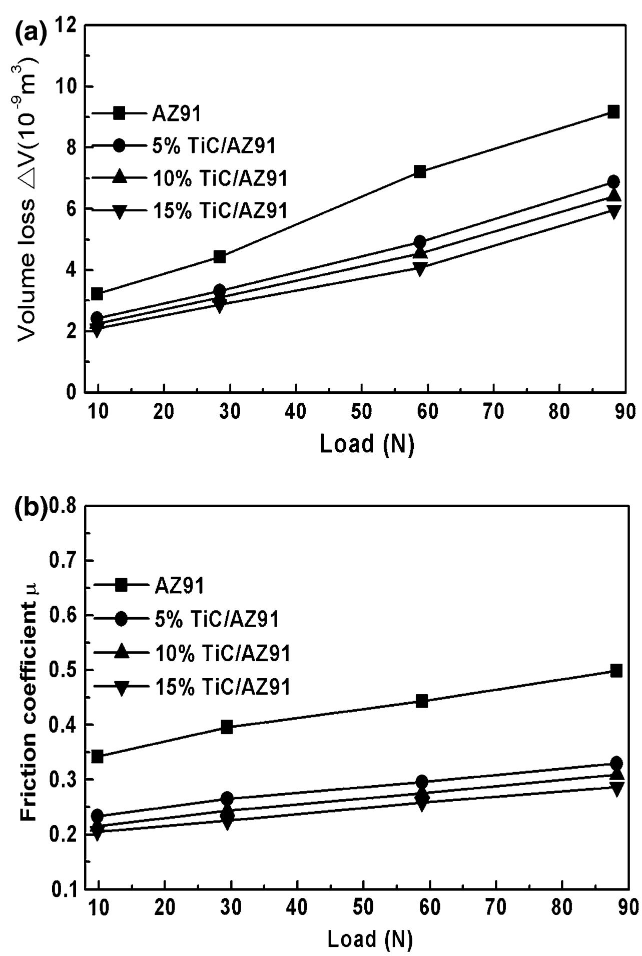

Fig. 3 The variation of (**a**) volume loss and (**b**) friction coefficient of AZ91 alloy and TiC_p/AZ91 composites with applied load

29.4 N and a sliding velocity of 0.419 m s^{-1}, respectively. There is a rapid increase in the volume loss of AZ91 alloy and TiC_p/AZ91 composites with the increase of wearing time (see Fig. 4a). The increase of friction heat with the increase of wearing time can cause rise of temperature in friction surface and increase the extent of adhesive wear. This may lead to a rapid increase in the volume loss of two kinds of materials with the increase of wearing time. Moreover, the increase rate of the AZ91 alloy is higher than those of the composites. The lower increase rates of the volume loss of the composites may be caused by the action of TiC particulates in supporting load and protecting matrix from wear during friction and wear.

Both the friction coefficient of AZ91 alloy and the TiC_p/AZ91 composites increases with increase of the wearing time, but the friction coefficient of the TiC_p/AZ91 composites increase slowly compared with AZ91 alloy (see Fig. 4b). With the increase of wearing time, the temperature of the friction surface rises, which induce the chemical reaction in the surface to form the oxide film and change the surface layer structure of wear specimens. These lead to increase of the friction coefficient of two kinds of materials. In addition, the changing of the surface layer structure of the composites with the increase of wearing time decreases due to the presence of TiC particulates. This maybe leads to lower increase rate of the friction coefficient of the TiC_p/AZ91 composites.

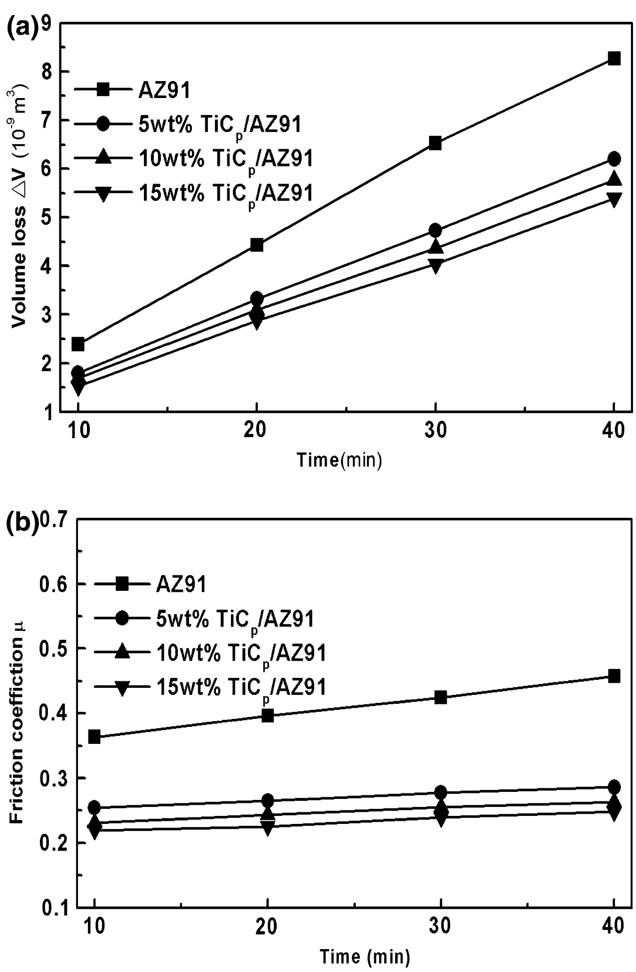

Fig. 4 The variation of (**a**) volume loss and (**b**) friction coefficient of AZ91 alloy and TiC_p/AZ91 composites with wearing time

Worn surface and wear debris analysis

Morphologies of the worn surface of AZ91 alloy, 5, 10 and 15 wt.% TiC_P/AZ91 composites under a load of 29.4 N, a wearing time of 20 min and a sliding velocity of 0.419 m s^{-1} are shown in Fig. 5a–d, respectively. It can be seen that a lot of parallel, continuous, and deep ploughing grooves are arranged on the wear surface of the AZ91 alloy, and there is an obvious adhesion phenomenon (see Fig. 5a). However, the ploughing grooves on the wear surface of the TiC/AZ91 composites get much shallower, finer, and not continuous, and there is a slight adhesion phenomenon (see Fig. 5b–d). The results indicate that the adhesive wear and abrasive wear of the composites decrease gradually with the increase of TiC content from 0 to 15 wt.% and the wear resistance of the composites is improved significantly.

Morphologies of the wear debris of the AZ91 alloy, 5, 10 and 15 wt.%TiC_p/AZ91 composites under a load of 29.4 N, a wearing time of 20 min and a sliding velocity of 0.419 m s^{-1} are shown in Fig. 6a–d, respectively. The wear debris from the AZ91 alloy and TiC/AZ91composites consist of plate-like shape debris and tiny wear particulates. Furthermore, the size of the wear debris from the AZ91 alloy is much larger than those from the TiC/AZ91 composites, and the wear debris from the TiC_p/AZ91 composites changes gradually small with the increase of TiC particulate content. From the morphology and size of the wear debris, the TiC particulates can serve as hard barriers that enhance the resistance to plastic deformation and relieve delamination and transfer of the massive matrix. According to XRD patterns of the wear debris of AZ91 and 15 wt.% TiC/AZ91, as shown in Fig. 7a–b, respectively, it is conformed that the wear debris of AZ91 consists of Mg, MgO and Fe, and the wear debris of 15 wt.% TiC/AZ91 consists of Mg, MgO, Fe and TiC. The presence of MgO in the debris of either AZ91 or 15 wt.% TiC/AZ91indicates that oxide reaction

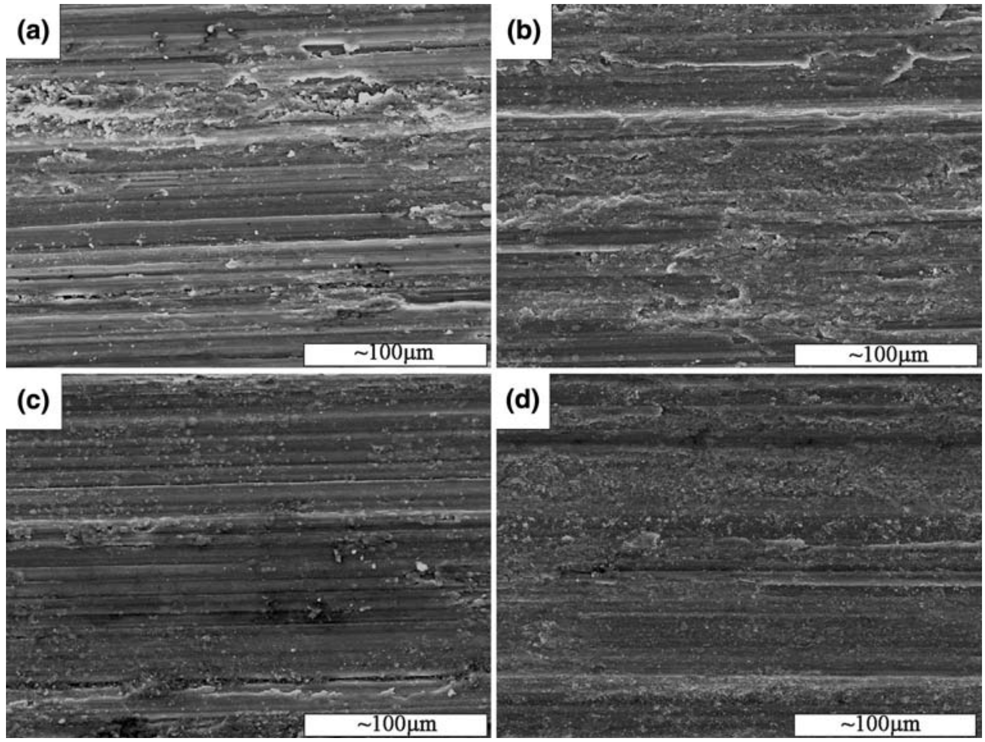

Fig. 5 Morphologies of the worn surface of (**a**) AZ91 alloy, and (**b**) 5, (**c**) 10 and 15 wt.% TiC_P/AZ91 composites under a load of 29.4 N, a wearing time of 20 min and a sliding velocity of 0.419 m s^{-1}

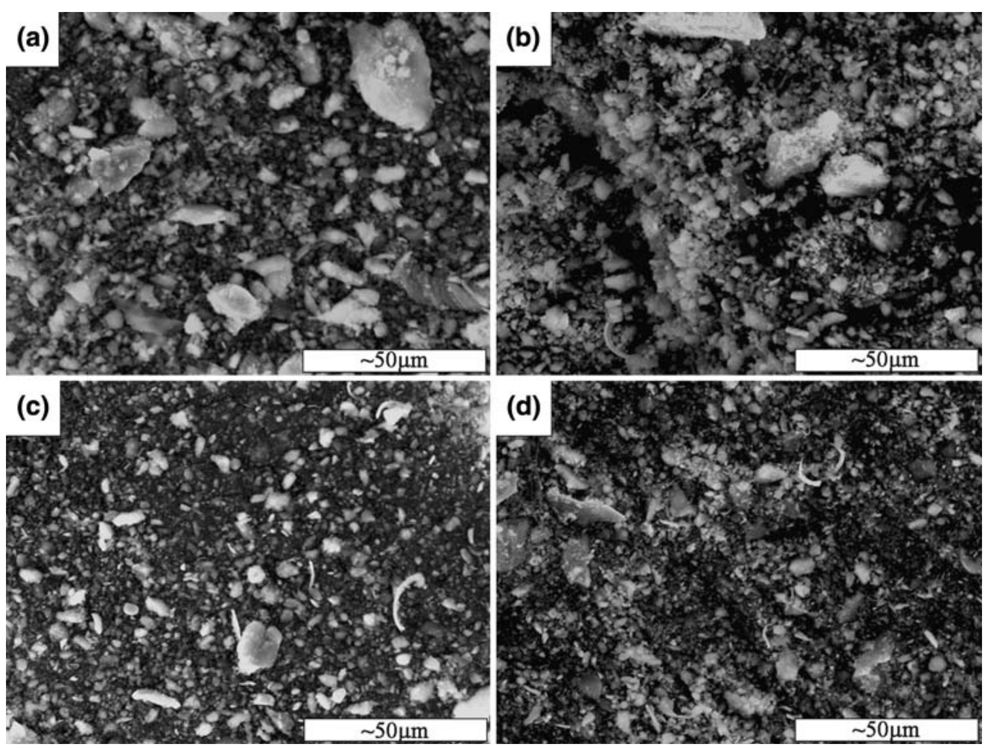

Fig. 6 Morphologies of the wear debris of (**a**) AZ91 alloy, and (**b**) 5, (**c**) 10 and 15 wt.% TiC_P/AZ91 composites under a load of 29.4 N, a wearing time of 20 min and a sliding velocity of 0.419 m s^{-1}

occurs during wearing test. The above results show that the wear behavior of the AZ91 alloy and the TiC/AZ91composites is characterized by ploughing, adhesion and oxidation.

Conclusions

AZ91 metal matrix composites reinforced with 5, 10 and 15 wt.% TiC particulates are fabricated by

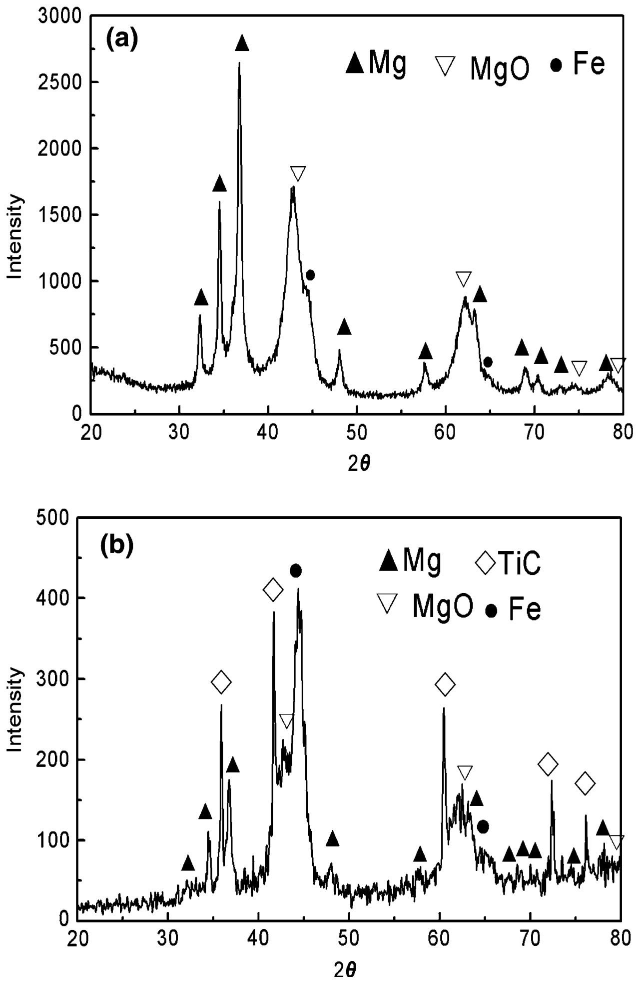

Fig. 7 XRD patterns of wear debris of (**a**) AZ91 alloy and (**b**) 15% TiC_p/AZ9 composite

TiC_p-Al master alloy process combined with mechanical stirring. The sliding wear behaviors of the AZ91 alloy and the TiC_p/AZ91 composites are investigated. The main conclusions are as follows:

(1) The microstructures of the composites all reveal the finer grains than that of the unreinforced AZ91 matrix alloy. Moreover, the hardness and wear resistance of the composites are improved greatly as compared with those of the unreinforced AZ91 matrix alloy.

(2) The wear resistance of the composites increase with increase of the TiC particulate content, while friction coefficient of the composites decrease with increase of TiC particulate content.

(3) The wear volume loss and friction coefficient of the composites as well as the unreinforced AZ91 matrix alloy increase with increase of applied loads or wearing time, but the increase rate of the composites is lower than that of the unreinforced AZ91 matrix alloy.

(4) The wear behavior of the unreinforced AZ91 matrix alloy and the composites is characterized by ploughing groove, adhesion and oxidation.

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