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Friction and wear behavior of TiC particle reinforced ZA43 matrix composites ①

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[Abstract] TiC/ZA43 composites were fabricated by XD^{TM} and stirring-casting techniques. The tribology properties of the unreinforced ZA43 alloy and the composites were studied by using a block-on-ring apparatus. Experimental results show that the incorporation of TiC particles improves the microstructure of ZA43 matrix alloy. The coefficient of friction μ and the width of worn groove decrease with the increase of TiC volume fraction φ(TiC). The width of worn groove and μ of the composite during wear testing increase with increasing the applied load. Metallographic examinations reveal that unreinforced ZA43 alloy has deep ploughing grooves with obvious adhesion phenomenon, whereas TiC/ZA43 composites have smooth worn surface. Delamination formation is related to the fatigue cracks and the shear cracks on the surface.

[Key words] ZA43 alloy; TiC particle; fine equiaxed grain; friction and wear
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1 INTRODUCTION

Zinc-aluminum (Zn-Al) based alloys found considerable industry use during the past few years. This is primarily due to their excellent castability, wear resistance, and good mechanical properties. Therefore, they can compete satisfactorily with other foundry alloys such as copper, aluminum or cast iron. Despite the attractive room-temperature properties of Zn-Al alloys, its elevated temperature mechanical properties were found to be unsatisfactory, and the application is restricted.

To improve the elevated temperature properties of Zn-Al alloys, researchers have used ceramic materials to reinforce the alloys since the mid-1980s. Commonly, the addition of ceramic reinforcement to a metal matrix improves strength and stiffness, but at the expense of ductility. Compared to the continuous fiber-reinforced composites, particulate-reinforced MMCs offer several advantages such as improved anisotropy, ease of fabrication and lower cost.

In contrast to aluminum-matrix composites, however, less attention is paid to zinc-matrix composites[1~3]. In the case of particulate reinforcement, Cornie et al[4] and Karni et al[5] indicated that the presence of SiC particles in ZA alloys leads to a substantial improvement in elastic modulus and hardness. The tribological properties of Zn-based MMCs have received little attention. Muthukumarasamy and Seshan[3] indicated that the wear resistance of ZA27 alloy is improved significantly by the alumina fiber reinforcement. To the best of our knowledge, there is no work reported in the literature concerning the wear behavior of particle-reinforced ZA43 alloy. It is the aim of this work to determine the wear behavior of the ZA43 alloy reinforced with TiC particles under continuously lubricated condition, and to investigate the effects of load, particle volume fraction on friction and wear properties.

2 MATERIALS AND EXPERIMENTAL TECHNIQUES

2.1 Materials

Al powder (purity 99.6%, size 47 μm), Ti powder (purity 99.4%, size 50 μm) and graphite (commercial high-grade purity) were mixed in certain proportion in a ball mill for 24 h, and were pressed into blocks. The pressed blocks were sintered in a furnace under an argon atmosphere to fabricate Al-TiC preforms, and then the preforms were added into Al-Cu molten alloy, followed by addition of zinc and stirring. The chemical composition of the matrix alloy is shown in Table 1. After being stirred and refined, the molten alloy was poured into a permanent mold at about 750 ℃ to prepare specimens of TiC/ZA43 composites. A scanning electron microscope was employed to observe TiC morphology, while a metallographic microscope to observe the microstructure of TiC/ZA43 composites.

2.2 Wear test

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Table 1 Composition of matrix alloy (mass fraction, %)

Al	Cu	Mg	Fe	Sn	Pb	Zn
43	2.5	0.02	0.012	0.0014	0.0016	Balance

Wear specimens were prepared from the cast ingots, with gauge of 12.35 mm × 12.35 mm × 19 mm. Prior to the tests, the samples were mechanically polished. Wear tests were carried out under continuously lubricated sliding conditions on a block-on-ring tester (model MHK-500). The sliding ring with a diameter of 49.24 mm and a width of 12.7 mm was made of GR15 bearing steel with hardness of HRC60. The wide rectangular faces of the block specimens were put in line contact with the sliding ring. Grade 20 hydraulic oil with the rate of 110 cm^3/min was injected into the contact region throughout the test. The tests were carried out at a sliding velocity of 1.55 m/s and at various constant loads applied by a load arm between 1545 N·m and 2526 N·m. The sliding time was 10 min. The friction coefficient was measured through a load cell. The width of worn groove was measured on macroscopical morphology of worn surface by using an optical microscope with a reading device. The worn surfaces were observed with a scanning electron microscope (SEM).

3 RESULTS AND DISCUSSION

3.1 Microstructure of TiC/ZA43 composites

The microstructure of TiC/ZA43 composite is shown in Fig. 1. In this figure, the light regions represent the primary cores of aluminum-rich α' which are surrounded by dark regions of zinc-rich β phase. As-cast microstructure of ZA43 alloy mainly consist of coarse dendritic crystal α' and β (zinc rich) phase[6], and the incorporation of TiC in the Zn-43Al alloy has a significant effect on the size of dendrites in the matrix alloy. As shown in Fig. 1, as-cast microstructure of TiC/ZA43 composite is mainly made up of equiaxed grain. During solidification, TiC is supposed to act as nucleation sites for primary phase in the matrix alloy. Both TiC and primary α' are face centered cubic lattice. Lattice parameter of TiC is 0.43189 nm[7], while α' 0.4000 nm[8], and lattice mismatch parameter δ is 7.97%, which conforms to coherent principle. Besides, defects existing on TiC surface, energy, temperature and concentration fluctuations in molten alloy make for TiC acting as heterogeneous nucleation sites for α' phase in ZA43 alloy.

3.2 Effect of reinforcement content

TiC particle, with high hardness and high modulus of elasticity[7], has the superstability and the function of reinforcement in ZA43 alloy matrix, so the strength, hardness and stiffness of the alloy were

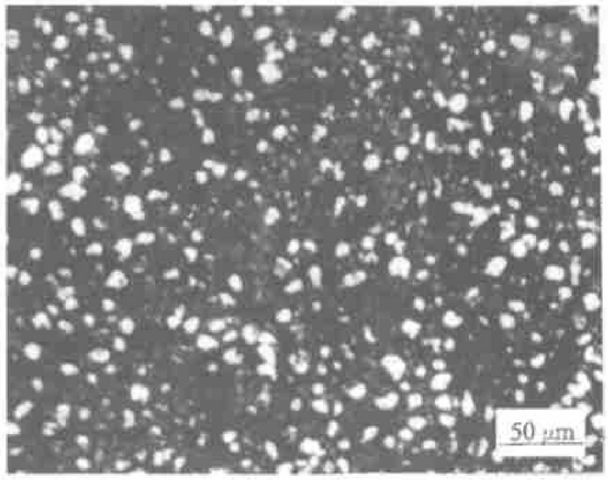

Fig. 1 Microstructure of TiC/ZA43 composite

improved. The higher the particle volume fraction is, the better the mechanical properties are[1]. Consequently it is difficult for the micro-protuberances on the steel ring to scratch the composite when the samples are rubbed against it, and the wear resistance of the alloy is improved.

The effect of TiC particle content on the friction coefficient of TiC/ZA43 composites is shown in Fig. 2 (a). The friction coefficient is observed to decrease gradually with the increase of TiC volume fraction, which means that the coefficient of friction between particle and steel ring is smaller than that between matrix and steel ring. Increasing reinforcers content reduces the contact area of the matrix with the coun-

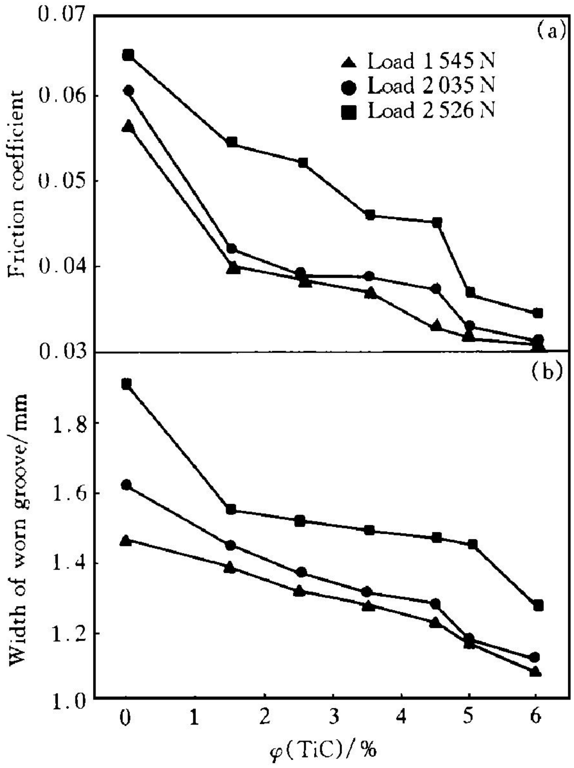

Fig. 2 Effect of TiC content on wear (a) and friction (b) properties

terface, thus minimizing the 'smearing effect' of high aluminum zinc-based alloy on the counterface surface, and resulting in smaller temperature increase at the sliding interface.

Fig. 2(b) shows the width of worn grooves on the specimens with different TiC content. The unreinforced ZA43 alloy has wider worn grooves, particularly under a load of 2526 N. However, the addition of only 1.5% TiC particle to the ZA43 alloy leads to a marked decrease in the width of worn groove at all normal loads; thereafter, the width of worn groove decreases almost steadily with increasing particle content. That is to say, the increase in TiC particle volume fraction improves the wear resistance of TiC/ZA43 composites.

3.3 Effect of applied load

As shown in Fig. 2(a), the friction coefficients of ZA43 alloy and TiC/ZA43 composites increase with the loads. Moreover, ZA43 alloy has a greater friction coefficient than TiC/ZA43 composites at all levels of loads. Fig. 2(b) also shows that the width of worn groove of ZA43 alloy and TiC/ZA43 composites increases with normal loads, but ZA43 alloy gives a greater rate of increase than TiC/ZA43 composites. These also indicate that the composites are of excellent wear resistance relative to matrix alloy.

Because of the inherent thermal expansion mismatch between the reinforcers and the matrix, when the composites cool down from manufacturing temperature to room temperature, the shrinkage of ZA43 matrix alloy is impeded by TiC particle[9]. As a result, compression stress is predominant in the direction perpendicular to TiC particles, which is adverse to microcracks extending in that direction. During wear process, the increase of applied load causes plastic deformation resistance of ZA43 decreasing due to friction heat on counterface increasing dramatically. As ZA43 has good toughness and fractures in ductile manner, the softening matrix is favorable for microcracks extending in ZA43 alloy. The increase of applied load results in oil film near contact surface becoming thinner and lubricated sliding condition deteriorating. Under this condition, lubricant starvation results in wear extent increasing. As can be seen from Zn-Al-2.5% Cu ternary phase diagram[10], when the alloy solidifies, solid solution α(Al) and precipitable intermetallic compound θ-$CuAl_2$ come into being, and θ-$CuAl_2$ coheres to the surface of TiC particle[11]. This indicates there exists a brittle layer between ZA43 matrix alloy and TiC particle. When applied load increases substantially, the brittle layer may fracture and TiC particles become dislodged and three-body abrasive wear is predominant.

3.4 Metallographic observation

Fig. 3 shows the morphologies of worn surface of ZA43 alloy and TiC/ZA43 composites tested under a load of 2035 N. It can be seen that a lot of parallel and deep ploughing grooves, interspersed by craters

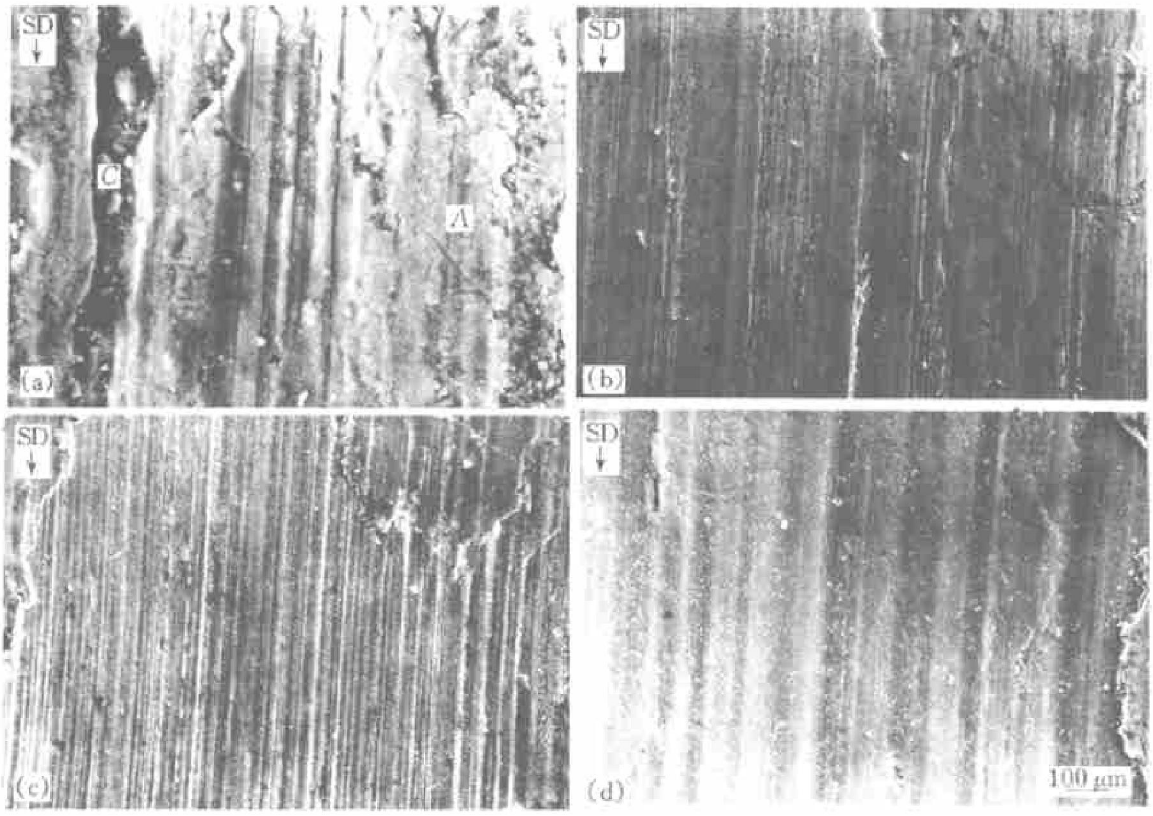

Fig. 3 SEM micrographs of worn surface of unreinforced ZA43 alloy (a) and TiC/ZA43 (b), (c), (d) under continuously lubricated condition
(a) —ZA43 alloy; (b) —1.5% TiC/ZA43; (c) —3.5% TiC/ZA43; (d) —6% TiC/ZA43

(Fig. 3(a), marked by *C*), are arranged on the worn surface of unreinforced ZA43 alloy, and there is an obvious adhesion phenomenon (as shown in Fig. 3 (a), marked by *A*). Adhesive wear is supposed to be predominant in this case.

During the wear process of TiC/ZA43 composites, TiC particles on the worn tracks bear normal pressure and shear pressure, thus the matrix is protected from severe wear. At the same time, particle dislocation strengthening and fine grain strengthening improve composite strength and toughness[12]. These enhance composites wear resistance effectively and prevent ZA43 matrix flowing plastically. Besides, some oil storage spaces exist among convex on the surface, and this provides a well lubricated condition. All the factors result in TiC/ZA43 having smooth worn surface (Fig. 3(b), (c) and (d)). Under this condition, grain abrasion is supposed to be predominant. Clearly, with increasing TiC content, the worn surfaces of TiC/ZA43 composites become relatively smooth and the ploughing grooves become much shallower.

3.5 Wear mechanism of TiC/ZA43 composites

As for TiC/ZA43 composites, dislodged TiC, abrasion dust and their mixture form abrasive particle. Wear resistance of TiC/ZA43 composites improves rapidly mainly because the existence of TiC and strengthened matrix impede abrasive particle penetrating the matrix. With low volume fraction of TiC in ZA43 alloy, abrasive particle can penetrate the matrix sufficiently, 'ploughing' the surface effectively. This is the reason for the observed increment of worn groove width. With increasing TiC content, the larger abrasive particle can not penetrate the ZA43 matrix alloy deeply. Even if smaller abrasive particle penetrate the matrix, the track is shallow. As a result, the plastic deformation is limited. Besides, the penetrating abrasive particles are prone to encounter TiC particles in the matrix. This is supposed to cause abrasive particle becoming blunted and deviating from worn cracks, which results in TiC/ZA43 composites having smooth worn surface, with no visible crater formation.

From the metallographic observations, the wear mechanisms of the unreinforced ZA43 alloy and TiC/ZA43 composites are postulated as shown in the schematic diagrams in Fig. 4 and Fig. 5. Fig. 4 shows the state of stress around an abrasive particle. Apparently, there exist normal stress and shear stress simultaneously in the matrix around abrasive particle, which causes sharp stress gradient near the particle. For the unreinforced ZA43 alloy, during wear process, due to tension-compression alternating stress, firstly slip lines come forth on contact area. Screw dislocations change their glide plane and cross slip takes place. Opposite dislocations counteracting each other activate dislocation source on primary glide plane to proliferate dislocation continuously. Accordingly slippage of slip lines increases, glide band broadens and deepens. Lastly a large amount of fatigue cracks perpendicular to the sliding direction in the rough are produced on matrix surface. At the same time, the contact surface induces plastic deformation by shear in the subsurface region. Such plastic deformation causes the dislocations to glide along their slip planes. In the severe wear region, the dislocation density tends to increase dramatically. The accumulation and the pile-up of dislocations lead to the nucleation of voids near the interface of the subsurface/substrate region. These voids then grow and coalesce to form subsurface cracks parallel to the sliding direction. Delamination of the deformed region from the specimen surface occurs when the fatigue cracks link together with the shear cracks (Fig. 5). The delamination shows a flake-like morphology with a smooth upper surface and granular under surface. The TiC particles in MMC is supposed to act as barriers to resist the plastic deformation of the matrix, thus delaying the nucleation and propagation of fatigue microcracks and shear microcracks in the matrix.

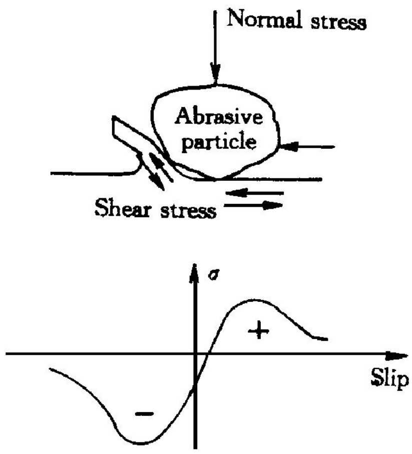

Fig. 4 State of stress around abrasive particle

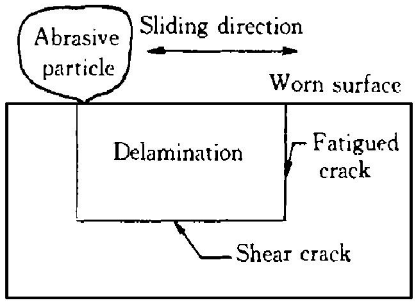

Fig. 5 Schematic diagram of delamination formation

4 CONCLUSIONS

1) TiC particles can act as nucleation sites for primary phase when ZA43 alloy solidifies, and have a significant effect on refining ZA43 alloy. TiC addition

improves granular morphology of ZA43 alloy, and the composites are made up of fine equiaxed grain.

2) The wear resistance of TiC/ZA43 composites is superior to that of ZA43 alloy. The friction coefficients decrease with increasing TiC content, and increase with increasing load. The widths of groove of ZA43 alloy and TiC/ZA43 composites decrease with increasing TiC content, and increase with increasing loads, but ZA43 alloy gives a greater rate of increase than TiC/ZA43 composite.

3) A lot of parallel and deep ploughing grooves interspersed by craters are arranged on the worn surface of ZA43 alloy, and adhesive wear is supposed to be predominant. The worn surfaces of TiC/ZA43 composites become smooth and grooves become much shallower, and a combination of abrasive and delamination wear is supposed to be predominant.

4) Delamination occurs when fatigue cracks link together with shear cracks. TiC/ZA43 composites have less delamination than unreinforced ZA43 alloy.

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