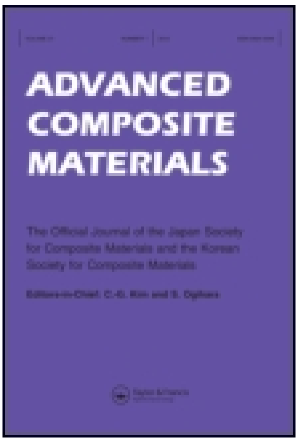

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Tribology properties of TiC_p/ZA43 composite under continuously lubricated sliding condition

XIE XIAN-QING [1,*], LIU JIN-SHUI [2] and ZHANG DI [1]

[1] *State Key Laboratory of Metal Matrix Composites, Shanghai Jiao Tong University, Shanghai, 200030, P.R. China*
[2] *College of Materials Science and Engineering, Hunan University, Changsha, 410082, P.R. China*

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Abstract—ZA43 alloys reinforced with TiC particles were fabricated by XD™ and stirring-casting techniques. The sliding friction and wear properties of the unreinforced ZA43 alloy and the composites under continuously lubricated condition were studied by using a block-on-ring apparatus. Experimental results showed that the addition of TiC particles was a very effective way of improving the microstructure and wear resistance of the matrix alloy. Both coefficient of friction (μ) and the width of worn groove decreased with the TiC volume fraction (V_f) increasing, and increased with the applied load increasing. Metallographic examinations revealed that unreinforced ZA43 alloy had deep ploughing grooves with obvious adhesion phenomenon, whereas TiC/ZA43 composites had smooth worn surface. Delamination formation was related to the fatigue cracks and the shear cracks on the surface. During the wear process, sub-surface micro-hardness values of ZA43 alloy and TiC/ZA43 composites give a different variation.

Keywords: TiC/ZA43 composite; continuously lubricated condition; tribology.

1. INTRODUCTION

Zinc-aluminum (Zn-Al) based alloys have found considerable industrial 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 alloy, 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 began to use ceramic materials to reinforce the alloys since the mid-1980s [1–3].

*To whom correspondence should be addressed. E-mail: xiexqsh@yahoo.com.cn

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 composite, however, less attention was paid to zinc-matrix composites [4–7]. In the case of particulate reinforcement, Cornie *et al*. [8] and Karni *et al*. [9] 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 [7] 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 powders (metallic purity 99.6%, 100 mesh), Ti powders (metallic purity 99.4%, 300 mesh) 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 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°C to prepare specimens of TiC/ZA43 composites. A scanning electron microscope was employed to observe TiC morphology, while a metallographic microscope was used for the microstructure of TiC/ZA43 composites.

2.2. Wear test

Wear specimens were prepared from the cast ingots, with size of $12.35 \times 12.35 \times 19\ mm^3$. Prior to the tests, the samples were mechanically polished. Wear tests

Table 1.
The composition of matrix alloy (wt%)

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

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 Nm and 2526 Nm. The sliding time was 10 min. The coefficient of friction 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 by a scanning electron microscopy (SEM). Microhardness of specimens after wear test was determined with an MXT-CX7 Vickers tester.

3. RESULTS

3.1. Microstructure of TiC/ZA43 composites

Figure 1 shows the SEM morphology of TiC particles in Al-TiC preform. It is clear that TiCs are spherical particles with nearly uniform size (1 μm or so). Microstructure of TiC/ZA43 composites is shown in Fig. 2. 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 consists of coarse dendritic crystal (α') and β (zinc rich) phase [10], and the incorporation of TiC in the Zn-43Al alloy had a significant effect on the size of dendrites in the matrix alloy. As shown in Fig. 2, as-cast microstructure of TiC/ZA43 composites is mainly made up of equiaxed grain. During solidification, most TiCs are supposed to act as nucleation sites for primary phase in the matrix alloy. Both TiC and primary α' are face-centered cubic lattice.

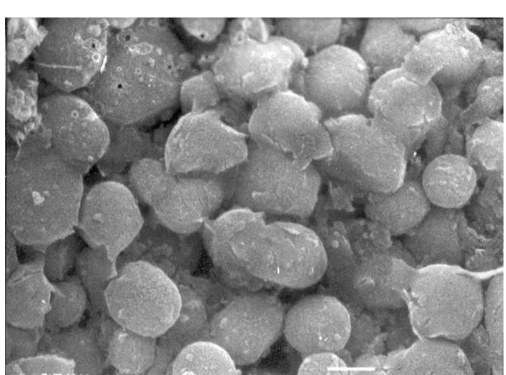

Figure 1. SEM morphology of TiC in Al-TiC preform.

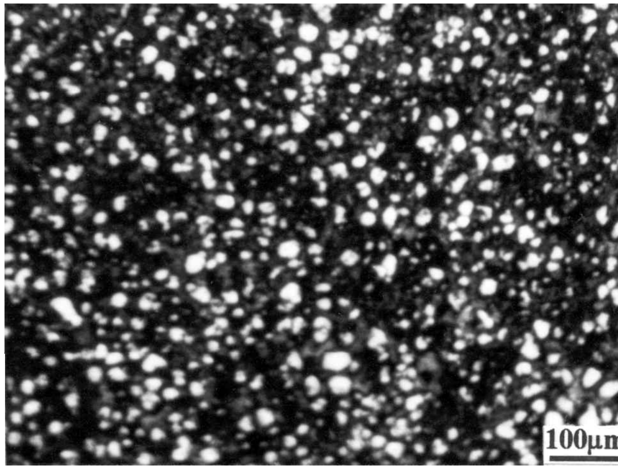

Figure 2. Microstructure of TiC/ZA43 composite.

The lattice parameter of TiC is 0.43189 nm [11], while α' equals 0.4000 nm [12]; the lattice mismatch parameter δ is 7.97%, which conforms to the coherent principle. Besides, defects existing on TiC surface, energy, temperature and concentration fluctuations in molten alloy make TiC act as heterogeneous nucleation sites for α' phase in ZA43 alloy. As described elsewhere, they exist mostly at the surface of the light region and in the grain of primary phase [13].

3.2. Effect of reinforcement content

TiC particle, with high hardness and high modulus of elasticity, has superstability and the function of reinforcement in ZA43 alloy matrix. As a result, the strength, hardness and stiffness of the matrix alloy were improved [12]. The greater the particle volume fraction, the better are the mechanical properties [5]. Consequently, it was difficult for the microprotuberances on the steel ring to scratch the composite when the samples were rubbed against it, and the wear resistance of the alloy was improved.

The effect of TiC particle content on coefficient of friction of TiC/ZA43 composites is shown in Fig. 3a. The coefficient of friction is observed to decrease gradually as the volume fraction of TiC increased, which means that the coefficient of friction between particle and steel ring is smaller than that between matrix and steel ring. Increased reinforcement content reduces the contact area of the matrix with the counterface, and it is supposed to minimize the ‘smearing effect’ of high aluminum zinc-based alloy on the counterface surface and results in smaller temperature increase at the sliding interface.

Figure 3b 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 vol% particle to the ZA43

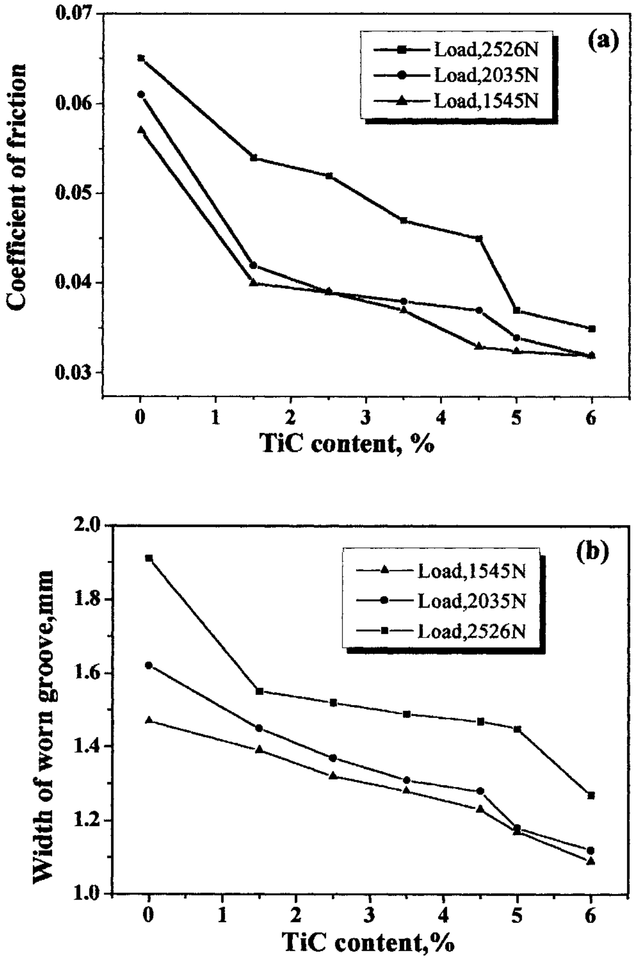

Figure 3. Effect of TiC content on wear and friction properties.

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 particle content increase. That is to say, the increase in TiC particle volume fraction improves the wear resistance of TiC/ZA43 composites.

3.3. Effect of the applied load

As shown in Fig. 3a, coefficients of friction of ZA43 alloy and TiC/ZA43 composites increase as the loads increase. Clearly, ZA43 alloy has greater coefficient of friction than TiC/ZA43 composites at all levels of loads. Figure 3b also shows that the width of worn groove of ZA43 alloy and TiC/ZA43 composites increases with normal loads. ZA43 alloy gives a greater rate of increase than TiC/ZA43 composite. These also indicate that the composite is of excellent wear resistance relative to matrix alloy.

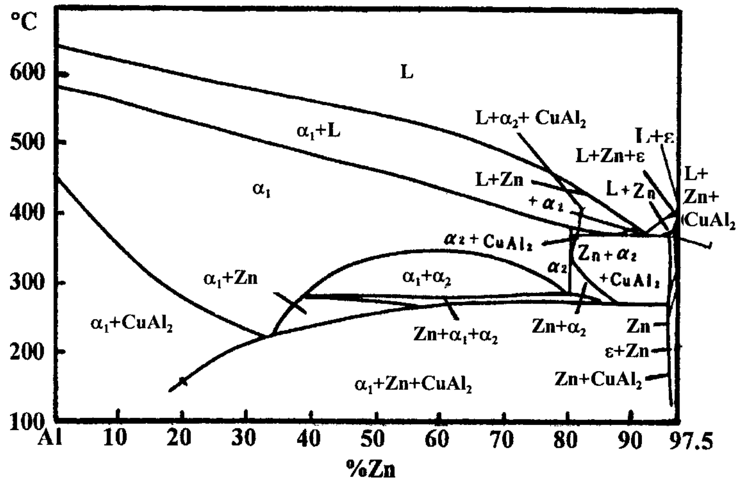

Figure 4. Zn-Al-2.5%Cu ternary phase diagram.

Coefficients of thermal expansion of TiC and ZA43 were 7.4×10^{-6}/K and 31.5×10^{-6}/K, respectively. When the composites cool down from manufacturing temperature to room temperature, inherent thermal expansion mismatch will take place between the reinforcement and the matrix [14]. The shrinkage of ZA43 matrix alloy is impeded by TiC particle and, as a result, compression stress is predominant in the direction perpendicular to TiC particles, which is adverse to microcracks extending on the particle surface. During the wear process, as for ZA43, applied load increasing causes plastic deformation resistance decrease due to dramatically increased friction heat on counterface. As ZA43 has good toughness and fractures in ductile manner, the softening matrix is favorable for microcracks extending in ZA43 alloy. Applied load increase results in oil film near contact surface becoming thinner and lubricated sliding condition deteriorating. Under this condition, lubricant starvation results in increase in the extent of wear. Figure 4 shows the Zn-Al-2.5%Cu ternary phase diagram [15]. It can been seen that 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 [16]. This indicates that there exists a brittle layer between ZA43 matrix alloy and TiC particle. When the 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

Figure 5 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 many deep ploughing grooves parallel to sliding direction (S.D. in Fig. 5), interspersed by craters (Fig. 5a, marked by C), are arranged on the worn surface of unreinforced ZA43 alloy. There

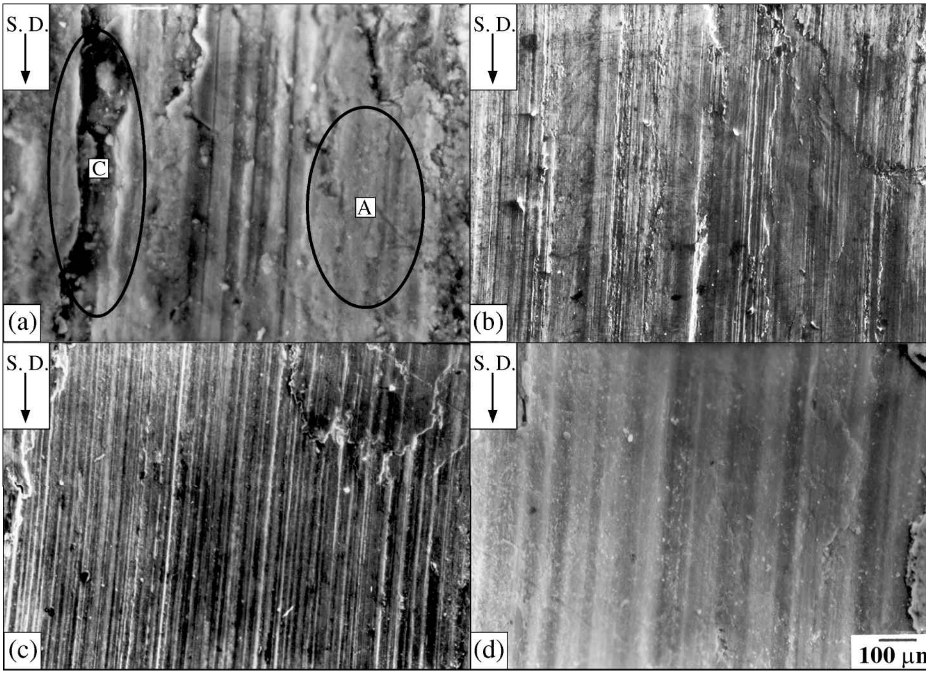

Figure 5. SEM micrograph of worn surface of unreinforced ZA43 alloy (a) and TiC/ZA43 (b, c, d) under continuously lubricated condition. (a) ZA43 alloy; (b) 1.5%TiC/ZA43; (c) 3.5%TiC/ZA43; (d) 6%TiC/ZA43. *S.D. denotes sliding direction.

is an obvious adhesion phenomenon (as shown in Fig. 5a, 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, and thus the matrix is protected from severe wear. The differences in CTE, lattice orientation and heat conductivity existing between TiC particle and ZA43 alloy cause the production of asymmetrical thermal contraction stress. When thermal stress is high enough, dislocations will come into being in the matrix near interface. They improve the strength of the composites by the Orawan mechanism. Furthermore, the incorporation of TiC decreases grain size (as shown in Fig. 2), and in present work, the greater the TiC content, the smaller is the grain size and then the more significant is the strengthening effect. For example, as compared with the tensile strength of 1.5 wt%TiC/ZA43 of 356 MPa, the tensile strength of 5 wt%TiC/ZA43 is 380 MPa [17]. These enhance composite wear resistance effectively and prevent ZA43 matrix from flowing plastically. Besides, some oil storage spaces exist among convex areas on the surface, and this provides a good lubricated condition. All these factors result in TiC/ZA43 having a smooth worn surface (Fig. 5b, c and d). During stable wear process under this condition, a combination of abrasive and delamination wear is supposed to be predominant. Clearly, with TiC content increasing, the worn surfaces of TiC/ZA43 composites become relatively smooth and the ploughing grooves become much shallower.

4. DISCUSSION

Wear resistance of TiC/ZA43 composites improves rapidly mainly because the existence of TiC and strengthened matrix impede abrasive particles penetrating the matrix. As for TiC/ZA43 composites, dislodged TiC, abrasion dust and their mixture form abrasive particles. With low volume fraction of TiC, abrasive particles can penetrate the matrix sufficiently, 'ploughing' the surface effectively. This is the reason for the observed increased width of worn grooves. With increasing TiC content, the larger abrasive particles cannot penetrate the ZA43 matrix alloy deeply. Even if smaller abrasive particles 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 the abrasive particles to become blunted and deviate from worn cracks, which results in TiC/ZA43 composite having smooth worn surface, with no visible crater formation.

From the metallographic observations, the wear mechanism of the unreinforced ZA43 alloy and TiC/ZA43 composites is postulated as shown in the schematic diagrams in Figs 6 and 7. Figure 6 shows state of stress around an abrasive particle. Apparently, there exist normal stress (σ) caused by normal load (P_2), and shear stress (τ) caused by shear force (P_1) simultaneously in the subsurface of the matrix around the abrasive particle. Near the contact point between the abrasive particle and the horizontal sliding surface, tension stress changes into compressive stress in the subsurface. Thus, there is a sharp stress gradient near the particle.

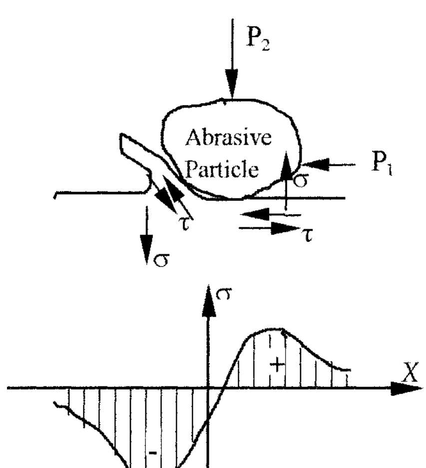

Figure 6. State of stress around the abrasive particle.

For the unreinforced ZA43 alloy, firstly slip lines emerge on the 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, and glide band broadens and deepens. Lastly, a large amount of fatigue cracks perpendicular to the sliding direction in the rough are produced on the 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 in the matrix 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. 7). The delamination shows a flake-like morphology with a smooth upper surface and granular under surface. The TiC particles in MMC are 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.

The microhardness values of the wear zone in the matrix as a function of depth below the sliding surface are shown in Fig. 8. It is noted that the indentation is made only on the metal matrix of the MMC specimens during the microhardness measurement. The hardness values of the subsurface deformed layer of unreinforced ZA43 alloy are considerably lower than that of the substrate. That is to say, softening of the matrix takes place in the subsurface region of ZA43 alloy, which is associated with the fatigue of surface asperities. In the case of MMC, TiC/ZA43 composite shows little variation in the hardness values between the subsurface layer and substrate region. During the wear process, friction heat near the abrasive surface increasing dramatically leads to grain coarsening and recrystallization in the composites. Besides, as described above, plastic deformation in matrix subsurface causes accumulation and the pile-up of dislocations, which produce voids and mi-

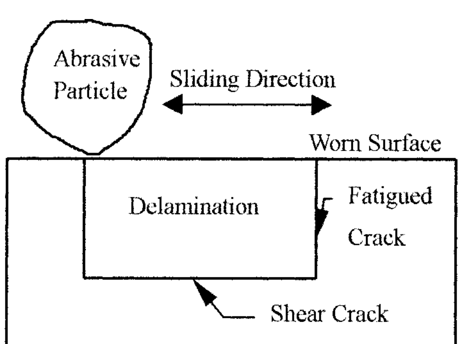

Figure 7. Schematic diagram of delamination formation.

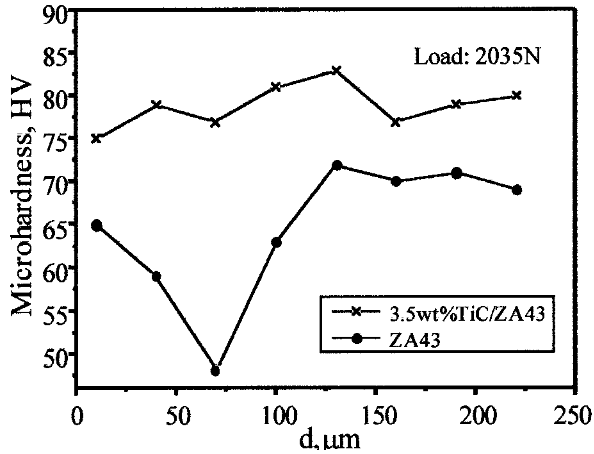

Figure 8. Cross-section microhardness of ZA43 and 3.5 wt%TiC/ZA43.

crocracks. All these result in surface microstructure of ZA43 alloy loosening and softening. In the case of TiC/ZA43 composites, TiC prevents dislocation gliding and increases recrystallization temperature [18], so delays the matrix-softening procedure.

5. 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. Coefficients of friction decrease with increasing TiC content, and increase with increasing load. The widths of groove of ZA43 alloy and TiC/ZA43 composites decrease with increase in TiC content, and increase with the loads, but ZA43 alloy gives a greater rate of increase than TiC/ZA43 composites.

(3) Many 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. Subsurface microhardness of unreinforced ZA43 alloy is lower than that of the substrate while TiC/ZA43 composite shows little variation between subsurface layer and substrate region.

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