International Journal of Metallurgical & Materials Engineering

Original Article   **Open Access**

Microstructure, Mechanical Properties and Wear Behaviour of Semi-solid Stir Casting SiC Reinforced Zn-40Al Based Composites

G. H. Geng[1], D.X. Wang[2], P. H. Xue[1], and F. Y. Dong[1,*]

[1]*School of Materials Science and Engineering, North Minzu University, Yinchuan, China*
[2]*Northwest Rare Metal Materials Institute, Yejin road,Shizuishan, China*

Abstract

The Zn-40Al composites with various contents of SiC were fabricated by the semi-solid stir casting process. The influence of the SiC on the microstructure, mechanical properties and wear behavior of the composites were investigated. Microstructure analysis shows that the microstructures of as-cast Zn-Al alloys are refined by the addition of SiC. However, with the increase of SiC content, a number of shrinkage porosity occur. The hardness of the composites increases with the increase content of SiC. The tensile strength of the composites declines significantly with the increase content of SiC. The most effective strengthening achieves in Zn-40Al/0.5wt.% SiC, with a maximum increment of 20% in tensile strength compared to non-SiC addition alloy. The overall results reveal that the composites possess similar friction coefficients but the abrasion loss is reduced to less than a tenth after adding 0.5% SiC.

Introduction

Metal matrix composites (MMCs) have many advantages compared with monolithic metals like higher specific modulus, higher specific strength, better properties at elevated temperatures and lower coefficient of thermal expansion [1]. MMCs have recently been used as critical structural applications duo to the combination of superior mechanical properties such as better tensile strength, elastic modulus, wear resistance and high temperature stability in comparison with the parent matrix alloys [2]. Zinc–aluminum (Zn-Al) alloys containing a spot of copper have prove to be possible as cost and energy effective substitutes for a variety of bronze, cast iron and aluminum alloys in bearings and as a structure material because of their higher strength, better wear resistance, lower casting temperature and abundant resources [3,4]. These alloys are used as an alternative material for bronze and aluminum alloys because of their good tribological properties. They have shown satisfactory service performance when used for the components such as bearings, punches and seals in which high mechanical properties and wear resistance are required [5].

In order to take advantage of and improve its basic properties, reinforcing Zn-Al alloys with ceramic materials has been explored [6]. The use of reinforcements such as silicon carbide (SiC) and alumina (Al_2O_3) has ameliorated in hardness, strength, specific strength, wear and creep resistance of Zn-Al based composites [7,8]. Among the plenty of manufacturing processes available for discontinuous MMCs, semi-solid stirring is generally accepted as a particularly promising route [9,10]. Its advantages lie in its simplicity, flexibility and applicability to a large quantity production and also it is the most economical of all available routes for MMCs [11]. Before semi-solid stirring process, SiC_p were pretreated. SiC_p was pretreated to form a layer of Cu film on it, which prevented the interfacial reaction with molten Zn-Al alloys and improved the wettability between the reinforcements and the matrix alloy.

In the present study, the Zn-40Al composites with different contents of SiC_p were successfully fabricated by semi-solid stirring technique. Subsequently, the effects of SiC_p contents on the microstructure, mechanical properties and wear behavior of the composites were investigated.

Experimental Procedure

Material

Commercial pure zinc (Zn-99.99wt. %) and aluminum (Al-99.97wt. %) were procured for the production of the Zn-40Al alloy to be produced as the matrix for the composite. The sample designations for the fabricated Zn-40Al based composites are presented in table 1. Chemically pure silicon carbide particles (SiC, 1μm), were selected as reinforcement for the composite productions with different contents. SEM images of untreated and Cu-coated SiC particles were shown in figure 1.

Material	Elements			
	Al	Cu	Mg	Zn
ZA40 alloy	38-41	2.0-2.5	0.01-0.02	Balance

Table 1: The chemical composition of Zn-40 Alallloy (in wt.%).

Fabrication of the composites

The fabrication of the Zn-40Al/SiCp composites was performed using semi-solid stir-casting process consisted of the following steps: (1) Zn-40Al alloy was molten at 700 °C in stainless steel crucible and then cooled to a semi solid state (at a temperature of about 510 °C); (2) The SiCp preheated at 500 °C to remove moisture and to improve wettability with Zn-Al alloy was added into the semi-solid matrix alloy, stirred at 850 r/min for 30 min; (3) The semi-solid slurry was then poured into a preheated container (480 °C) and allowed to solidify to obtain composite billets.

*Corresponding Author: Dr. Fu yuan Dong, School of Materials Science and Engineering, North Minzu University, Yinchuan 750021, China; E-mail: fydong@alum.imr.ac.cn

Microstructural examination

Microstructure observation was carried out by scanning electron microscope (SEM). The samples for the examination were metallographically polished and etched using hydrofluoric acid solution for 5 s before the microstructural investigation was carried out.

Mechanical testing

The hardness, tensile properties and wear behavior of the composites were evaluated using Brinell hardness testing, tensile testing, and wear testing, respectively. The specimens for hardness test were ground and polished before carrying out multiple hardness indentations. The hardness values within the range of ±2% were averaged to obtain the hardness value.

A universal tensile testing machine operated at a strain rate of 0.5 mm/min was used for the tensile testing of the composite samples which were machined as a bone-shape with a gauge length of 25 mm and a diameter of 5 mm. The samples were pulled in tension to fracture and stress-strain curves were generated for each sample in accordance with ASTM 8M-91 Standard (1991). The tensile properties evaluated from the stress-strain curves are yield strength, tensile strength and percent elongation. Multiple tensile tests were performed for each test composition of the composite to guarantee the reliability and reproducibility of the results.

Wear tests were carried out at RM (room temperature) with a wear testing equipment controlled by computer. The external diameter of the counterpart discs was 3 mm and it was made of induction quenched GCR15 steel, which had a hardness of HRC 60. Abrasion test were performed at a constant load of 1850 N. For each sample, the test was carried out at a constant sliding speed of 0.1 m/s for 25 min. Each wear sample was ultrasonically cleaned in acetone and weighed by an electronic balance with an accuracy of 0.1 mg before and after the wear test to measure the mass loss. The friction coefficient of the sample was recorded simultaneously by the computer. Three tests were carried out for each set of sample. The worn surfaces were analyzed by SEM.

Result and Discussion

Microstructural characterization

Figure 2 shows the microstructures of the Zn-40Al alloy and the selected Zn-40Al/SiC composites. The microstructure of the Zn-40Al alloy in the cast condition forms α-Al dendrites and Zn + η phase-rich in interdendritic spaces. The addition of copper influences the formation of intermetallic ε phases ($CuZn_4$) in the interdendritic regions. In the
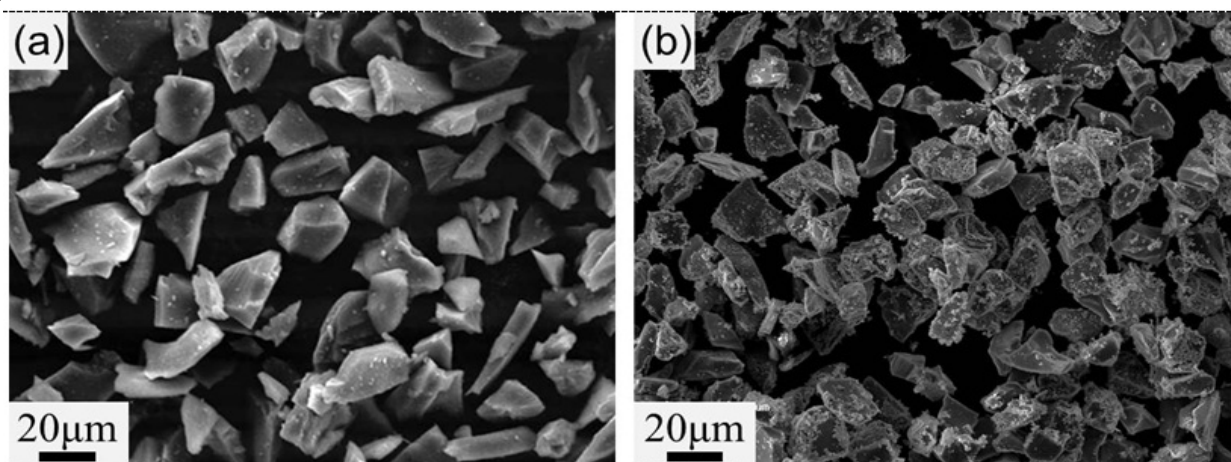

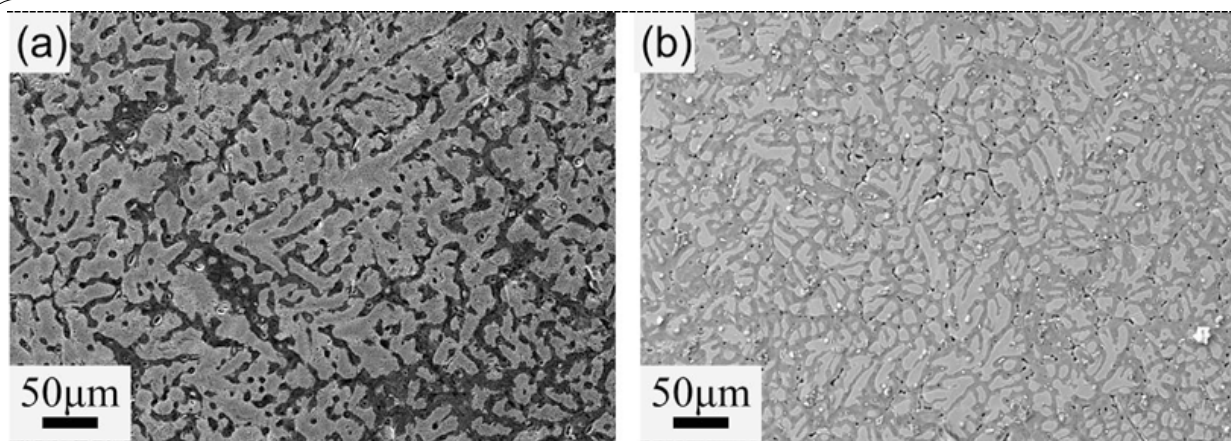Figure 1: SEM images of (a) untreatedand (b) Cu-coated SiC particles.

Figure 2: Representative micrograph showing (a) the Zn–40Al alloy microstructure, (b) the microstructure of the Zn–40Al based composite containing 0.5 wt% SiC.

composites with different contents of SiC, the microstructures appear very similar, consisting of the dendritic structure same with that of the Zn-40Al alloy matrix and well distributed reinforcing particles in the interdendritic regions. Regardless of the contents, dendrites percentages are slightly higher than in the Zn-40Al alloy without SiC. Nevertheless, the addition of SiC of the base alloy resulted in the occurrence of finer grains, same with the observation in the previous investigations [12-15]. Similarly, addition of SiC promotes a more uniform distribution of precipitates presence in the interdendritic regions. Similar microstructural features have been reported by Alaneme who worked on Zn-40Al based composites reinforced with bamboo leaf ash and silicon carbide. However, the density measurements showed that the composites contained some porosities, and the amount of porosity in the composites increased with the increasing content of the SiC (Table 2).

Mechanical behavior

The Brinell hardness of the composites and matrix alloy is given in Table 2. The relation between the particles content and the hardness of the composites was plotted in Figure 3(a). As compared to the Zn-40Al matrix alloy, the hardness of the MMCs was higher, indicating the addition of SiC particles increased the hardness of the Zn-Al alloy [16,17]. Furthermore, the hardness of the composites increased with increasing SiC content. The fine, hard and well dispersed SiC particulates was responsible for the improved hardness.

The profiles of ultimate tensile strength (UTS) of the composites as a function of SiC content were depicted in Figure 3(b). With the increase of SiC contents, the tensile strengths exhibited a tendency to decrease after the first rise. It indicated that compared with non-SiC addition alloy, adding 0.5% SiC can improve the tensile strength. When the alloy contains 0.5% SiC, the UTS value is 463 MPa and the YS is 460 HB. The improving amplitudes reach 19.6% and 27.1%, respectively. When adding 1.0% and 1.5% SiC, the tensile properties decline significantly compared to the composite with 0.5% SiC. And the total elongation (TE) decreases continuously with the increasing contents of SiC. The UTS increases from 387 to 463 MPa while the TE decreases from 2.4% to 1.1% after incorporating 0.5 wt. % in SiC particulates. The decrease in the TE of the composites with increasing SiC content may be due to the limited plastic deformation of the matrix by the particles and the deterioration of ductile matrix content when the amount of porosity in the composites increased with the increasing content of the SiC. Moreover, the residual stresses generated due to the large difference in thermal expansion coefficient between the matrix and particles would probably contribute to the brittle nature of the composites [18].

The fracture morphologies of the Zn-40Al/SiP$_p$ composites are shown in figure 4. The presence of small dimples and tearing ridge indicates that the fracture mechanism of the composite with 0.5% SiC is principally ductile fracture containing some brittle failure. It can be seen that the amount of dimples decrease with the increase of SiC content while the flat regions exhibit an opposite tendency. It is worth noting that, in addition to the fracture features mentioned above, shrinkage cavities can also be found on the fracture surfaces of the composites with 1.0% and 1.5% SiC, which can be attributed to the dendrite segregation in non-equilibrium solidification process.

The strength and hardness of the Zn-40Al alloy and Zn-40Al/SiC$_p$ composites are listed in Table 2. The ratio of hardness to strength has been plotted as functions of the SiC content, as shown in figure3 (c). The ratio of hardness to strength is approximately equal to 3 in theZn-40Al alloy and Zn-40Al/0.5%SiP$_p$ composites, but obviously increased to high value in the Zn-40Al/1.0%SiP$_p$ and Zn-40Al/1.5%SiP$_p$ composites.
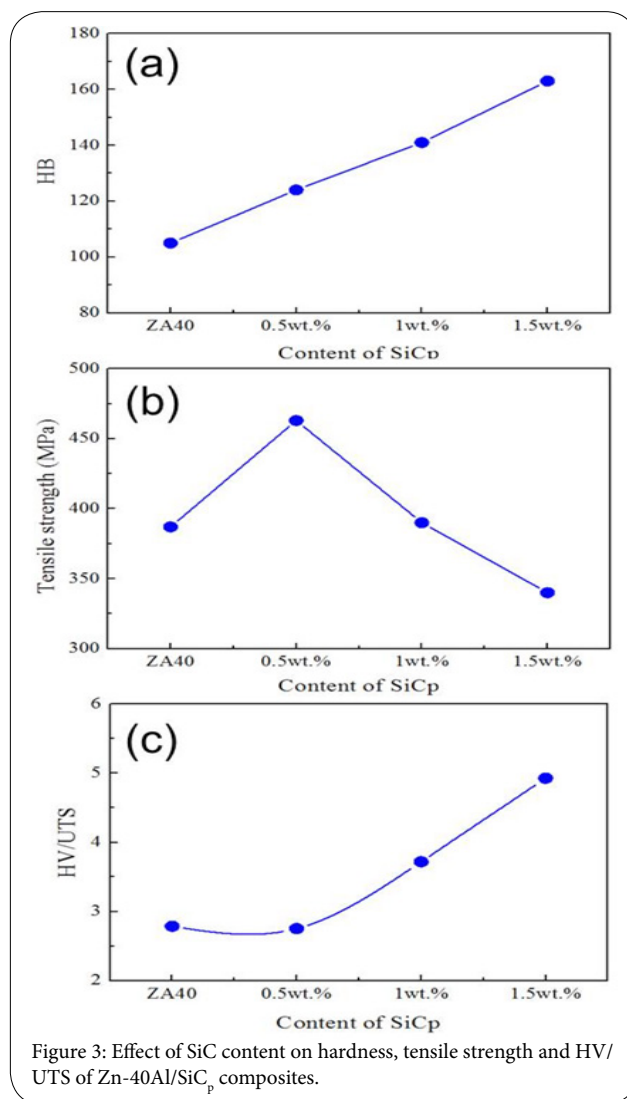

Figure 3: Effect of SiC content on hardness, tensile strength and HV/UTS of Zn-40Al/SiC$_p$ composites.

	HB	UTS (MPA)	YS	EL	HV (MPa)	HV/UTS	Porosity (%)
ZA40	105	387	362	2.4	1078	2.79	2.86
0.5wt.%	124	463	460	1.1	1274	2.75	3.07
1.0wt.%	141	390	388	0.2	1450.4	3.72	4.73
1.5wt.%	163	340	339	0.1	1675.8	4.93	7.22

Table 2: Material properties of the Zn-40Al alloy and reinforced-composite samples.
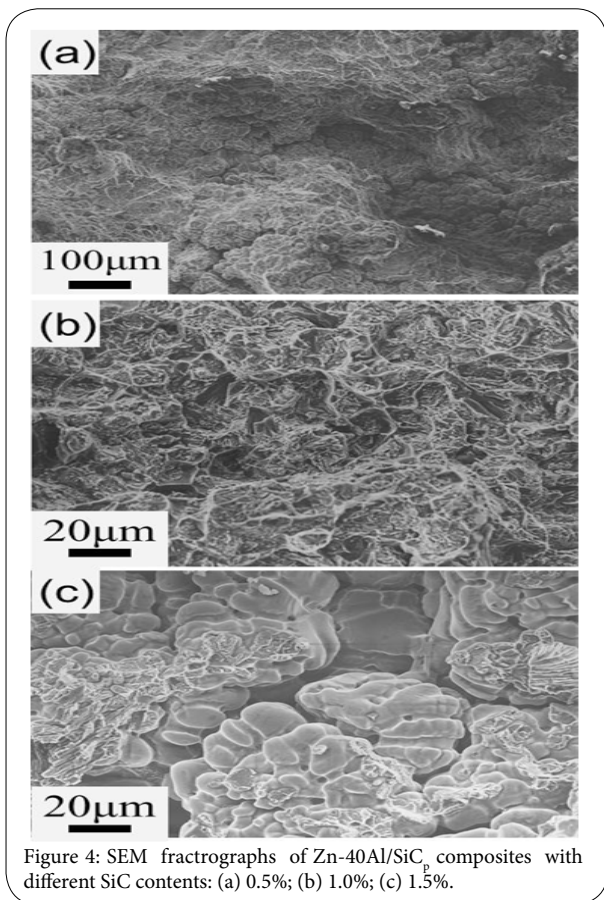
Figure 4: SEM fractrographs of Zn-40Al/SiC$_p$ composites with different SiC contents: (a) 0.5%; (b) 1.0%; (c) 1.5%.

Following the analyses of Zhang et al. [19], the ratio of hardness to strength should be related to the difference in the shear ability of various materials, which can be schematically plotted versus the value α [20]. This parameter ($α=τ_0 /σ_0$) related with strength of materials was induced in the Ellipse criterion proposed by Zhang and Eckert to explain the deformation and failure behaviors in different materials [19-21], where $σ_0$ and $τ_0$ are critical normal and shear fracture strength. It can be concluded from these results above that the mechanical characteristics in the Zn-40Al alloy and Zn-40Al/SiCp composites should be mainly affected by these variations, as illustrated in figure 5. As the increase of SiC content, the dimension of crystals is smaller and the dendrite segregation becomes aggravation for ZA40-1.5% SiC. The brittle fracture and obvious shrinkage cavities can be seen in figure 4 (c). For the present Zn-40Al/1.0%SiP$_p$ and Zn-40Al/1.5% SiP$_p$ composites, the slip stress in the interior of grains increases so that the critical shear stress along the localized shear bands is greatly enhanced [22,23].The critical normal stress decreased with the appearance of these pore- and crack-like defects. Accordingly, the ratio of hardness to strength can be affected by the refined structures and the induced porosity through influencing the $τ0$ and $σ_0$.

Wear behavior of the composites

The effect of sliding distance on the coefficient friction of Zn-40Al alloy and Zn-40Al/SiP$_p$ composites is seen in figure 6. It is shown that with an increase in sliding distance, there is a gradual decrease in coefficient of friction for both the matrix alloy and the composites. Similar results have also been reported by other researchers [24,25]. At the beginning of the test run, contact between the sliding surfaces occurs at only a few highly protruding asperities [26]. In the case of the Zn-40Al alloy, asperity junction took place in the initial stage
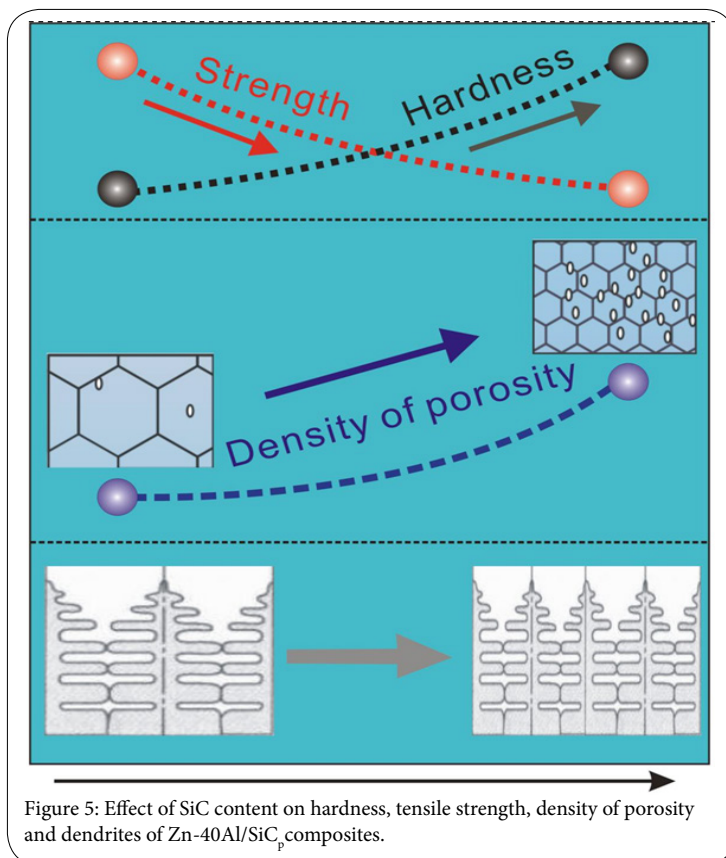

Figure 5: Effect of SiC content on hardness, tensile strength, density of porosity and dendrites of Zn-40Al/SiC$_p$ composites.

due to the low hardness and inferior strength. Local tearing occurred in the vicinity of the asperities and resulted in coarse debris which can be confirmed by the following wear surfaces analysis. However, the friction coefficient values (Figure 6) do not show any marked sensitivity to the variation of the SiC content in the composites. The friction coefficient values of the composites are within the range of 0.25 and 0.35.

Coefficient of friction values of Zn-40Al alloy and the developed composites are given in Table 3.It is obvious that the friction coefficient is slightly declined by adding 0.5% SiC particles into the matrix. Further increasing the content of SiC to 1.0% results in a significant increase. Composite containing SiC (1.0% and 1.5%) having higher friction coefficient values. An increase of 31.4% and 11.0 % in

the coefficient of friction is observed for 1.0 wt% and 1.5 wt% SiC composites respectively compare to the matrix alloy without SiC.

The variation of the abrasion loss of Zn-40Al40/SiC$_p$ composites as a function of SiC content is depicted in figure. 7. It is observed that the abrasion loss decreases dramatically from alloy to composites, and slightly decreases with the increase of SiC content. Incorporating 0.5wt% SiC reduces the abrasion loss from 0.0266 g of the alloy to 0.0021 g of the composite. This can be explaned by the higher hardness of the composites and the good interfacial bonding between the matrix and reinforcement [27]. Furthermore, as shown in figure 8, the extent of direct metal-to-metal contact can be ruduced by SiC, which play the role of bearing load for protecting the matrix during the sliding process.
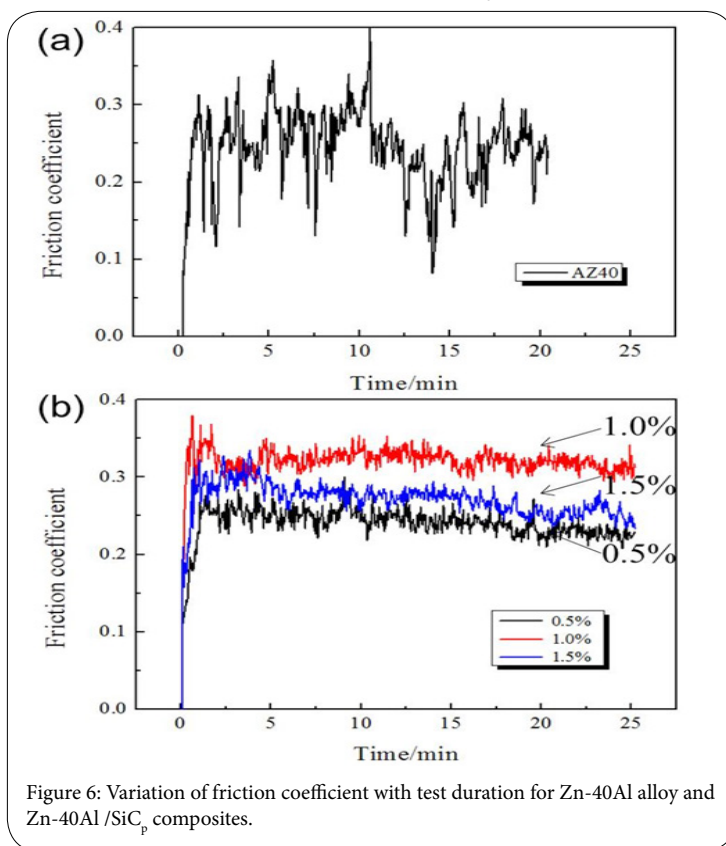

Figure 6: Variation of friction coefficient with test duration for Zn-40Al alloy and Zn-40Al /SiC$_p$ composites.
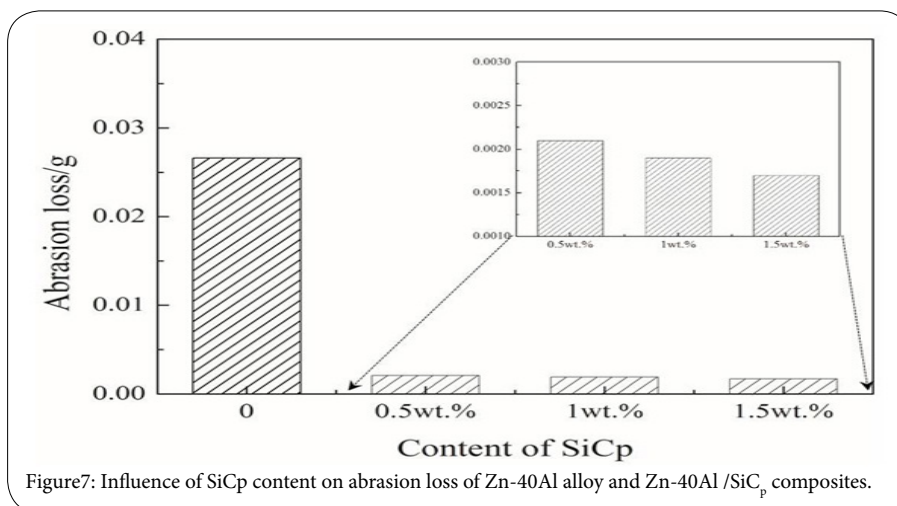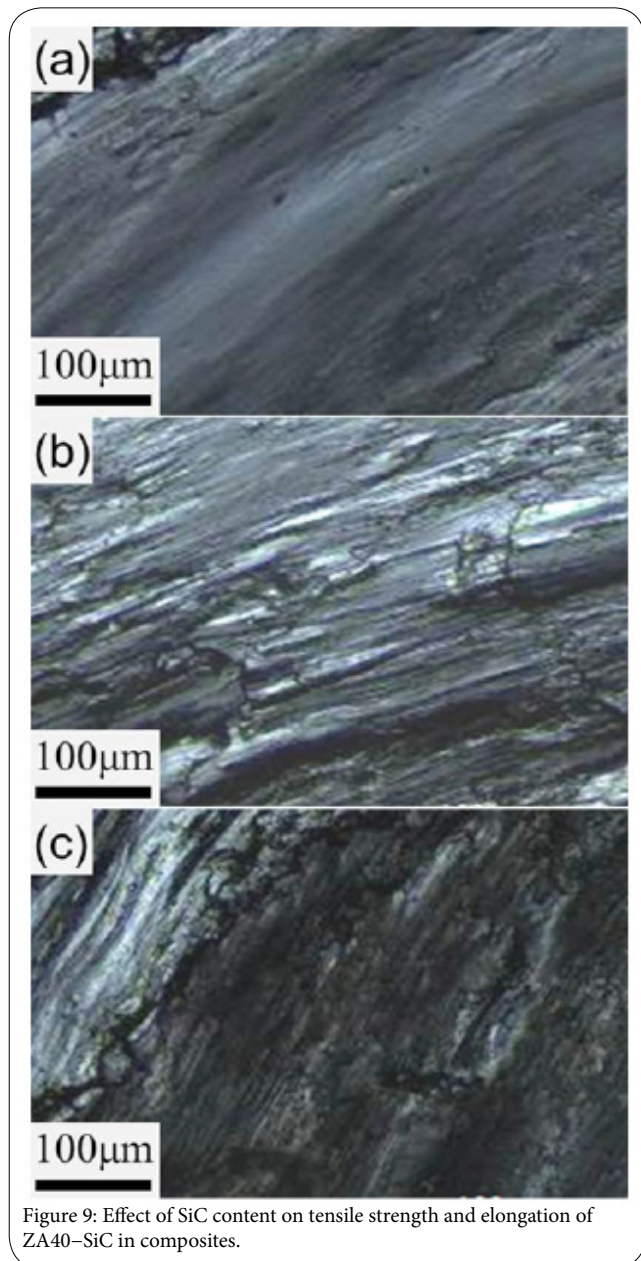

Figure7: Influence of SiCp content on abrasion loss of Zn-40Al alloy and Zn-40Al /SiC$_p$ composites.

Figure 8: Friction surface schematic of Zn-40Al/SiC$_p$ composites.

Figure 9: Effect of SiC content on tensile strength and elongation of ZA40–SiC in composites.
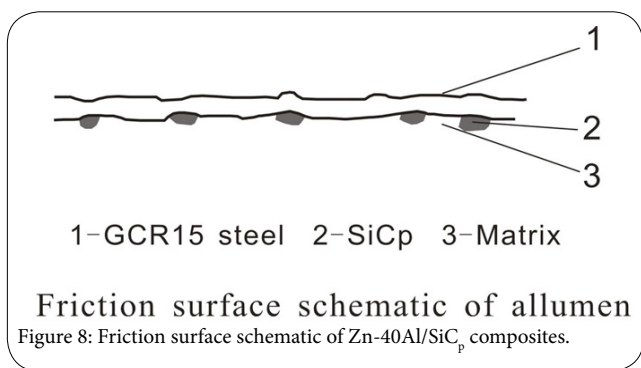
The SEM photographs of worn surfaces of Zn-40Al matrix alloy and Zn-40Al/SiC$_p$ composites can be seen in figure 9. There is a difference in the morphology of worn surfaces between the composites and the matrix alloy. The composites show fine grooves on the surface, whereas shallow and widergrooves are observed in case of the matrix alloy, which can explain the lower wear rates of the composites.

Porosity has a negative effect on their mechanical properties, which is the distinguishing feature of sintered materials. The influence of porosity on the wear behaviour of materials depends on the wear conditions and is not clearly identified. In the present investigation, these are not studied. Under certain conditions and depending on the pore size, porosity is observed to be beneficial for wear resistance by entrapping the wear debris and preventing the formation of large abrasive agglomerates. Pour filling superficially reinforce the material and result in diminishing plastic deformation and particle detachment around the pores.

From the results and discussions above, the major conclusions are summarized as follows:

1. The microstructures of the composites are similar, consisting of the dendritic structure of the Zn-40Al alloy matrix with fine dispersed SiC. After adding SiC, the microstructures of Zn-Al alloys are refined. However, with the increase of SiC content, a number of shrinkage porosity occurs. The most effective refining appears in Zn-40Al-0.5% SiC. Adding SiC could refine the grain and abate the dendritic grainsby strongly pinning dislocations and subgrain boundary.

2. The hardness of the composites for all the composites were much higher than the Zn-Al alloys, and increased with the increase of SiC content in the composites.

3. The tensile strength and yield strength of the composite with 0.5 wt% of SiC were higher than the Zn-Al alloys, but decreased with the increase of SiC content in the composites, with a maximum reduction of 8.5% in tensile strength.

4. The wear resistance ability of the composites increases with increase in the weight percent of SiC. As much as 90% decrease in abrasion loss was obtained for the SiC reinforced Zn-40Al composites containing 0.5 wt% SiC.

Funding

Data Availability Statement

The data used to support the findings of this study are included within the article.

Competing Interests

The authors declare that they have no competing interests.

References

1. Ranganath G, Sharma SC, Krishna M (2001) Dry sliding wear of garnet reinforced zinc/aluminium metal matrix composites. Wear 251: 1408-1413.

2. Kumar P, Xu C, Langdon TG (2006) Mater. Sci Eng A 429:324.

3. Tjong SC, Chen F (1997) Wear behavior of as-cast ZnAl27/SiC particulate metal matrixcomposites under lubricated sliding condition. Metall Mater Tran A 28: 1951-1955.

4. Babic M, Slobodan M, Dzunic D, Jeremic B, Ilija B, et al. (2010) Tribological behavior of composites based on ZA-27 alloy reinforced with graphite particles. Tribol Lett 37: 401-410.

5. Bobic B, Bajic N, Jovanovic MT, Bobic I (2009) Microstructureand mechanical properties of Zn25Al3Cu based composites withlarge Al2O3 particles at room and elevated temperatures. Metall. J Mater Eng 15: 245-255 .

6. Xu Z, Yan J, Zhang B, Kong X, Yang S (2006) Behaviors of oxide film at the ultrasonic aided interaction interface of Zn–Alalloy and Al2O3p/6061Al composites in air. Mater Sci Eng A 415: 80-86.

7. Mitrovic´ S, Babic´ M, Bobic´ I (2007) ZA-27 alloy composites withAl2O3 particles. Tribol Ind 29: 35-41.

8. Bobic´ B, Vencl A, Babic´ M, Mitrovic´ S, Bobic´ I (2014) The influence of corrosion on the microstructure of thermally treatedZA27/SiCp composites. Tribol Ind 36: 33-39.

9. NAI SM L, GUPTA M (2002) Influence of stirring speed on the synthesis of Al/SiC based functionally gradient materials. Composite Structures 57: 227-233.

10. Cook AJ, Werner PS (1991) Pressure infiltration casting of metal matrix composites. Materials Science and Engineering: A 144: 189-206.

11. Hashim J, Looney L, Hashmi MSJ (1999) Metal matrix composites: Production by the stir casting method. Journal of Materials Processing Technology 92-93: 1-7.

12. Hong-wei Z, Lin G, Li-na G, Lu-jun H (5010) Effects of SiC particle pretreatment and stirring parameters on the microstructure and mechanical properties of SiCp/Al-6.8Mg composites fabricated by semi-solid stirring technique. Materials Science and Engineering A 528: 513-518.

13. Valdez S, Campillo B, Perez R, Martinez L, Garcia HA (2008) Synthesis and microstructural characterization of Al-Mg alloy-SiC particle composite. Materials Letters 62: 2623-2625.

14. Murthy BS, Thakur SK, Dhindaw BK (2000) On the infiltration behavior of Al, Al-Li and Mg melts through SiCp bed. Metallurgical and Materials Transactions A 31: 319-325.

15. Tjong SC, Ma ZY (2000) Microstructural and mechanical characteristics of in situ metal matrix composites. Material Science and Engineering R 29: 49-113.

16. Chen T, Yuan C, Fu M, Ma Y, Li Y (2009) Friction and wear properties of castingin in-situ silicon particle reinforced ZA27 composites. China Foundry 6: 1-8.

17. Tjong SC, Chen F (1997) Wear behavior of as-cast ZnAl27/SiC particulate metal matrix composites under lubricated sliding condition. Metall Mater Tran A 28a: 1951-1955.

18. Chen F, Wang T, Chen Z, Mao F, Han Q, et al. (2015) Microstructure, mechanical properties and wear behaviour of Zn-Al-Cu-TiB2 in situ composites. Trans Nonferrous Met Soc China 25: 103-111.

19. Zhang P, Li SX, Zhang ZF (2011) General relationship between strength and hardness Materials. Science and Engineering A 529: 62-73.

20. Zhang ZF, He G, Eckert J, Schultz L (2003) Fracture mechanisms in bulk metallic glassy materials Phys Rev Lett 91: 045505.

21. Zhang ZF, Eckert J (2005) Unified tensile fracture criterion. Phys Rev Lett 94: 094301.

22. Dong FY, Zhang P, Pang JC, Chen DM, Yang K (2013) Optimizing strength and ductility of austenitic stainless steels through equal-channel angular pressing and adding nitrogen element. Materials Science & Engineering A 587: 185-191.

23. Dong FY, Zhang P, Pang JC, Ren YB, Yang K, et al. (2015) Strength, damage and fracture behaviors of high-nitrogen austenitic stainless steel processed by high-pressure torsion. Scripta Materialia 96: 5-8.

24. Thakur SK, Dhindaw BK (2001) The influence of interfacial characteristics between SiCp and Mg/Al metal matrix on wear, coefficient of friction and microhardness. Wear 247: 191-201.

25. Ramesh CS, Ahamed A (2011) Friction and wear behaviour of cast Al 6063 based in situ metal matrix composites. Wear 271: 1928–1939.

26. Kumar S, Chakraborth M, Subramanya Sarma V, Murty BS (2008) Tensile and wear behaviour of in situ Al−7Si/TiB2 particulate composites. Wear 265: 134-142.

27. Ramesh CS, Ahamed A (2011) Friction and wear behaviour of cast Al 6063 based in situ metal matrix composites. Wear 271: 1928-1939.