Friction and wear properties of casting in-situ silicon particle reinforced ZA27 composites

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Abstract: The effects of silicon particle content and testing temperature on friction and wear properties of casting in-situ silicon particle reinforced ZA27 composites were investigated. The wear mechanisms were mainly discussed by observations of both worn surfaces and their side views. The results indicated that the variations of wear resistance with increasing of silicon particle content, at all of the testing temperatures applied, showed a similar tendency with a manner of non-monotonous change. It was surprised that the wear resistance decreased with the increase of silicon particle content from 2 vol.% to 5 vol.%, while it increased when the content was less than 2 vol.% or more than 5 vol.%. Similarly, the friction coefficient also did not change monotonously. The dominative wear mechanism changed from a relatively severe regime of plastic deformation accompanied by adhesion wear, then to a very severe regime of severe plastic deformation induced wear, and finally again to a relatively mild regime of smear accompanied by abrasive wear as the silicon content increased. The wear resistance always decreased with elevating testing temperature, but the decrease ranges were different for the composites with different silicon contents. The friction coefficients changed irregularly for the different composites with the increase of testing temperature. Correspondingly, the wear mechanism alternated from a mild regime of smear accompanied by abrasive wear to a severe regime of plastic deformation accompanied by adhesion wear.

Key words: in-situ composite; silicon particle; friction and wear; wear mechanism; hardness

Zinc–aluminum alloys containing small amount of copper have been observed to be possible as cost- and energy-effective substitutes for a variety of ferrous and non-ferrous alloys owing to their higher strength, better wear resistance, lower casting temperature and abundant resources [1,2]. Unfortunately, dimensional instability and inferior elevated temperature properties seriously restricted their applications only to temperatures below 100°C [1-3]. The most promising way to improve these shortcomings has been to incorporate or to generate thermally stable microconstituent particles to form zinc-based composites. Adding high melting point silicon element to form in situ silicon particle reinforced composites has been considered as one of the most potential methods [4]. In addition, this is a way hopefully to further improve wear resistance [4-13].

The friction and wear properties of silicon particle reinforced ZA40 based composites have been comprehensively investigated, but some viewpoints from different researchers are contrary each other [5-12]. In addition, the existing works also have not involved the wear behaviors at elevated temperatures. The research on the ZA40 based composites indicated that the wear resistance and hardness increased with the increasing of Si content up to 2 wt.% due to the strengthening of uniformly distributed fine silicon particles, and then decreased with the further increase of Si content due to the agglomeration of silicon particles and the increase of average distance between them [14]. The results from Prasad [7] showed that the hardness always increased with increasing silicon content from 2 wt.% to 4 wt.%, while the wear resistance decreased because of the increased crack sensitivity imparted by silicon particles. A quench-ageing treatment increased the hardness and strength but decreased the wear resistance due to the transition of wear mechanism from smearing to scratch [6]. However, the investigation from Prasad [8] showed that quench-ageing could increase the wear resistance. He attributed this to the relief of residual stress, increased degree of uniform distribution of various phases and improved compatibility of silicon particles with the matrix. Comparatively, investigation about silicon particle reinforced ZA27 based composites is relatively scarce. The wear resistance and hardness of ZA27 based composites, similar to those of ZA40 based composites [5,8], also increased with increasing silicon content from 1 wt.% to 2 wt.% [9,10]. Wear performance was optimum when the silicon particles were larger in diameter than the thickness of lubricant film, but
small enough that they might be embedded in the wear surface and be covered by the surface film \[11\]. Wear resistance and anti-friction of a spray deposited composite with 5 wt% silicon were 8.1 and 2.4 times higher than that of the corresponding casting ZA27 alloy, respectively \[12\].

In this paper the effects of silicon particle content and testing temperature on the friction and wear properties of ZA27 based composites were studied. The wear mechanisms under variable conditions were mainly concluded after observing worn surfaces and side views of the worn surfaces.

1 Experimental process

The ZA27 based composites reinforced by silicon particles in this work were prepared by liquid casting method using pure aluminum, pure zinc, pure magnesium, Al-22Si alloy and Al-44%Cu alloy (percentage by weight). The nominal composition of the ZA27 alloy matrix was 26%–28%Al, 1.7%–2.0%Cu, 0.2%Zr, 0.02%–0.04%Mg (percentage by weight). Because of the low solubility of silicon in aluminum and zinc and the special solidification manner of this kind of composite \[14,15\], it can be assumed that all of the silicon element could be precipitated in form of primary silicon particles during solidification. Composites with different contents of silicon particles, ranging from 2 vol% to 13 vol% were melted at 780 °C, then modified at 610 °C by 0.3 wt.% red phosphorus, followed by degassing using argon gas at 750 °C, and finally poured at 750 °C into a steel mould to form 130 mm long and 15 mm diameter rods. For the purpose of comparison, some of the ZA27 alloy rods were also prepared by following the alternative sequence of melting at 650 °C, degassing and pouring at 600 °C.

Wear specimens with 5 mm diameter and 16 mm long were machined from the as-cast rods. Wear testing was performed on a pin-on-disc machine under sliding speed of 0.4 m/s and load of 3 kg. The counterparts were machined from 45# steel with hardness about 27 HRC. Three test temperatures including room temperature, 60 °C and 100 °C were employed. Each of the specimens was held for 10 min at these testing temperatures and then performed the tests at the corresponding temperatures. The weight-loss resulting from was the average of three specimens. The worn surfaces and side surfaces of the worn specimens were observed on a scanning electron microscope (SEM). Hardness of the composites was examined using HBRVU-187.5 hardness tester and hardness of the surface films and of sub-surface films was measured using HVS-1000 micro-hardness tester. The resulting hardness was also the average of three examinations.

2 Results and discussion

Figure 1 shows the variations of weight-loss and friction coefficient of the composites with silicon particles under variable testing temperatures. It can be found that the wear resistances of the composites under different testing temperatures changed in a similar tendency, a non-monotonous increase tendency with the increase in silicon content. They initially increased when the silicon content was below 2 vol.%, then decreased and finally continuously increased when the content was up to 5 vol.%. As the temperature increased, the wear resistances of all of the composites basically decreased. But the decrease ranges were different for the composites with different silicon contents. As for the friction coefficients, they also did not change monotonously as the silicon content increased at each of the testing temperatures. But their general change tendencies with the silicon content were similar, initially increased and then decreased. As the testing temperature increased, the friction coefficients of the composites with the different silicon contents changed differently. This phenomenon has no rule to be found.

![Fig. 1 Variations of weight-loss (a) and friction coefficient (b) of the composite with silicon particle content](image-url)

It is well known that the hardness of a material always can reflect its wear resistance to some extent. The present result indicated that the hardness of the composites continuously decreased with the increase of silicon content (Fig. 2). The increase of porosities with the silicon content should be the main reason which gave this result \[13\]. The agglomeration and spacing increase of silicon particles with increasing silicon content might be another reasons \[5\]. This was different from
the other investigators’ results [5-7], and also was not consistent with the irregular variation of wear resistance with the silicon content as shown in Fig. 1(a). So in this work, the wear behaviors of the composites could not be well interpreted by their hardness values.

**2.1 Effects of silicon content on wear mechanisms and the resulting wear behaviors**

In order to verify the effect of silicon content on wear behaviors, the worn surfaces and their side surfaces of the composites with different silicon contents under testing temperature of 100°C were observed.

Figure 3 shows the micrographs of their typical worn surfaces. The worn surface of the ZA27 alloy (without silicon addition) was seriously damaged and covered by some laminar structures formed from severe plastic deformation of the surface material. And, the parts of the laminar structures were scratched (Fig. 3(a)). This means that plastic deformation induced wear and adhesion wear were the main wear mechanism for the ZA27 alloy because the surface material was severely softened from the high ambient temperature and the friction induced heat.

For the composite with 2 vol.% silicon particles, the elevated temperature mechanical properties, such as hardness and strength, would be strengthened by the uniformly distributed small silicon particles [7,15]. Therefore, its ability to resisting plastic deformation at elevated temperature was improved and thus its wear resistance was enhanced (Fig. 1(a)). Accordingly, the damage degree of the worn surface was weakened and the surface appeared in a smooth form (Fig. 3(b)). Together with the previous investigations about wear properties of silicon particles reinforced Zn-Al based composites [5,6,10], it can be proposed that smear wear was the dominative mechanism for this composite. In this wear regime, the contact surface of the composite was hardened due to iterative plastic deformation and also oxidized due to high temperature. Thus, a compact hard layer formed on the worn surface to resist the nether matrix from wearing [16].

![Fig. 2 Variation of hardness of the composites with silicon particle content](image)

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![Fig. 3 SEM micrographs of worn surfaces of the composites with 0 vol.% (a), 2 vol.% (b), 5 vol.% (c), 13 vol.% (d) silicon particles tested at 100°C.](image)
When the silicon particle content increased up to 5 vol.%, the number and size of the silicon particles obviously increased (Fig. 4(a))\cite{15}, which enhanced the fracture susceptibility of the composite\cite{7}. In addition, the size of the silicon particles was still very small (5–7 µm) although they obviously grew up compared with those in the composites with 2 vol.% silicon particles\cite{15}. The particles on or close to the worn surface were easily covered by the matrix due to plastic deformation and did not play a role of directly loading against the counterpart. So the wear resistance obviously decreased (Fig 1(a)). The worn surface presented lots of wide and smooth grooves (Fig. 3(c)), which should form from plastic deformation of the surface film driven by protuberances on the counterpart. Therefore, severe plastic deformation induced wear should dominate for this composite.

As the silicon content further increased, the silicon particles gradually grew up (Fig. 4(b)) and the tendency of the particles to be covered would decrease. As a result, the role of the silicon particles to improve wear resistance gradually brought into play. So the wear resistance increased and the weight-loss decreased (Fig. 1(a)). In this case, a compact hard layer would form under the protection of silicon particles. That is to say that the dominative wear mechanism would gradually change from the plastic deformation induced wear to smear wear with the further increase in silicon content \cite{6,11}. Of course, the silicon particles embedded in or close to the worn surface would fracture or debond from their surrounding matrix due to stress accumulation and could be taken as abrasive to induce the abrasive wear. It thereby can be suggested that the smear accompanied by abrasive wear would be the dominant regime as the silicon content further increased. This can be demonstrated by the micrographs of worn surface of the composite with 13 vol.% silicon particles, which shows a smooth and planar surface on which lots of thin and straight grooves uniformly distributed (Fig. 3(d)). The characteristics of smooth and planar surface are the feature of smear wear and the uniform distribution of thin and straight grooves are the feature of abrasive wear\cite{5,6,10,20}.

Therefore, it can be suggested that the wear mechanism would change from a relatively severe regime of plastic deformation accompanied by adhesion wear to a mild regime of smear, then to a very severe regime of severe plastic deformation induced wear, and finally again to a relative mild regime of smear accompanied by abrasive wear as the silicon particle content increased up to 13 vol.% at the testing temperature of 100°C.

Figure 5 shows side views of the corresponding worn surfaces indicated by Fig. 3, which can give more information about the wear behaviors and more evidences to support the above discussion. Figure 5(a) presents that only a plastic deformation layer can be found for the ZA27 alloy. But for the composite with 2 vol.% silicon particles, in addition to the plastic deformation layer, the other two layers, i.e., the black surface layer and the fine-grained subsurface layer, can be seen (Fig. 5(b)). The result from the microhardness examination showed that the black surface layer was very hard, with hardness up to 285 HV. But the fine-grained layer was very soft with hardness only 77 HV, far lower than that of the unaffected zone (165 HV). As discussed in the above paragraph, the black hard layer formed from repeated deformation and oxidation of the surface material. However, the fine-grained subsurface layer might originate from recrystallization of the deformed subsurface material\cite{16}. The fracture of the silicon particles in the subsurface layer and debonding from their surrounding matrix could result in forming lots of cracks, which led to this layer quite loose and soft although the grains were very fine. Figure 6 obviously shows that one silicon particle fractures (marked by arrow). It can be expected that the small-sized silicon particles in the fine-grained layer were resulted from fracture of the original large-sized particles. In addition, cracks can be seen around the small-sized particles shown in Fig. 6. Results from Zhu’s investigations about stress-induced phase transformation of Zn-Al based alloy also indicated that the structure with such fine particles had low stress resistance at temperature little higher than the room temperature\cite{18,19}. Comparatively, the worn
The surface layer of the ZA27 alloy could be easily wiped away by the counterpart and both the black hard surface layer and fine grained loose subsurface layer could not form (Fig. 5(a)).

For the composite with 5 vol.% silicon particles, its side view of worn surface includes two layers, fine-grained surface layer and deformed subsurface layer (Fig. 5(c)). It can be seen that the fine-grained layer is composed of laminar structures, which is different from that of the composite with 2 vol.% silicon particles (Fig. 5(b)). In contrast, the speed of the surface material being wiped off for this composite was relatively higher than that for the composite with 2 vol.%, so the strain in the surface layer was lower and the resulting recrystallization was not so thoroughly and more characteristics of plastic deformation were maintained. The dendrites in the surface layer were elongated along the sliding direction and appeared in form of the laminar structure (Fig. 5(c)). When the silicon content further increased, as discussed above, the silicon particle size obviously increased [15], and then the possibility of the particles in the surface layer being covered by matrix could decrease. A black hard layer gradually formed on the fine-grained layer due to the protection of the large size silicon particles and, a three-layered microstructure similar to that of the composite with 2 vol.% silicon particles formed (Fig. 5(d)). Correspondingly, the wear resistance increased with the further increase of silicon content (Fig. 1(a)). Therefore, it can be concluded that the microstructural evolution of worn surface layer with the silicon content is well consistent with the variation of the wear resistance depending on the
corresponding wear mechanism.

It can be seen that the friction coefficients increased with increasing silicon content up to a value and then decreased from the point under each of the testing temperatures (Fig. 1(b)). This trend is similar to the Savaskan’s finding in his investigation about silicon particle reinforced ZA40 composites [5]. In this case, the strengthening role of the silicon particles to the matrix should increase with increasing silicon content up to a value (2 vol.% at room temperature and 7 vol.% at 60°C and 100°C) although the strength and hardness of the composites decreased [15]. This strengthening role can be mainly explained as the obstruction of the particles to the plastic deformation of the matrix. It thereby can be expected that the friction force would be increased as the silicon content increased, and thus the friction coefficient increased. But when the silicon content increased up to a level, as discussed above, the proportion of the abrasive wear to the whole wear increased as the silicon content further increased. It can be suggested that the friction force originated from rolling of the abrasive was smaller than that resulted from the deformation of the surface materials. Therefore, the friction coefficient decreased as the silicon content exceeded a level.

2.2 Effects of testing temperature on wear mechanisms and the resulting wear behaviors

Similarly, in order to verify the effect of testing temperature on wear behaviors of the composites, this work gives out the observation of the worn surfaces and their side surfaces of the composite with 5 vol.% silicon particles under the conditions of variable testing temperatures by using SME (Figs. 7 and 8). As shown in Fig. 1(a), the variation amplitude of wear resistance of this composite with the testing temperature was the largest, so the effect of testing temperature on the wear behavior can be obviously illustrated by observation results on this composite. Figure 7(a) presents the micrographs of the worn surface at room temperature, showing a relatively smooth and planar surface on which some thin and straight grooves distributed. This is similar to that shown in Fig. 3(d), indicating that smear accompanied by abrasive wear dominated. Accordingly, the side view of the worn surface is also similar to that of the corresponding composite, a hard black surface layer formed except a loose fine-grained subsurface layer and a plastic deformation layer (comparing Figs. 8(a) with 5(d)). It should be noted that there were some cracks at the interface between

![Fig. 7 SEM micrographs of worn surfaces of the composite with 5 vol.% silicon particles tested at room temperature (a) and 60°C (b).](image1)

![Fig. 8 SEM side views of worn surfaces of the composite with 5 vol.% silicon particles tested at room temperature (a) and 60°C (b).](image2)
the hard black layer and the loose fine-grained layer (Fig. 8(a)). These cracks might be originated from porosities, fracture and debonding of the silicon particles, and finally formed through propagation driven by the loading and friction forces.

Figure 9 obviously shows that a large crack originated from the fracture and debonding of silicon particles. These cracks would connect with the cracks perpendicular to the worn surface and a part of the hard black layer would desquamate. The cracks perpendicular to the worn surface could form from fatigue. When the temperature increased to 60°C, the worn surface shows some wide grooves and is very similar to that at 100°C (comparing Figs. 7(b) and 3(c)). The differences are that the grooves at 60°C were less smooth and the plastic deformation was obviously smaller. These implied that the plastic deformation accompanied by adhesion wear is gradually becoming to be dominated due to softening as the temperature increased, but it is less serious than that at 100°C. The similar view of side worn surface to that at 100°C also demonstrated that the deformation induced wear was the dominative wear mechanism (comparing Figs. 8(b) with 5(c)). Therefore, it can be concluded that the dominative wear mechanism would change from a relatively mild regime of smear accompanied by abrasive wear to a severe regime of plastic deformation accompanied by adhesion wear as the testing temperature increased from room temperature to 100°C.

However, the variations of the friction coefficients with the variable testing temperatures for the composites with different silicon contents changed differently, (Fig. 1(b)). Unfortunately, there was no appropriate rule in the current study to explain the phenomenon. This is resulted from comprehensive interactions between the composite microstructural characteristics and testing conditions, which will be verified in the next work.

The wear behaviors for the cases of the other two temperatures or of the other composites with different silicon contents can also be discussed by applying the similar ways discussed above. But it must be noted that the variation ranges of the weight-loss with the silicon content at the different testing temperature were different (Fig. 1(a)). It is well known that the room-temperature mechanical properties of some metal matrix composites reinforced by ceramic particles may be lower than those of the corresponding matrix alloys because the ceramic reinforcements can destroy the alloy matrix continuity. But their elevated-temperature mechanical properties are always higher because the strengthening role of the reinforcements is relatively higher than the impairing role, and the strengthening role usually increases as the reinforcement content increases. Therefore, the decrease range of weight-loss with the increase of silicon content up to 2 vol% or from 5 vol% to 13 vol.% increased as the testing temperature elevated and the difference in the weight-loss values at the different temperatures decreased as the silicon increased (Fig. 1(a)). But for the composites with silicon particle content from 2 vol% to 5 vol%, because of the increased fracture susceptibility and the softening role from the raised testing temperature, the decrease range of wear resistance significantly increased as the temperature raised (Fig. 1(a)).

3 Conclusions

(1) The wear resistance of the silicon particle reinforced ZA27 composites did not monotonously increased as the silicon particles content increased, but initially increased, then decreased and finally again increased. The friction coefficient initially increased and then increased with increasing silicon particle content.

(2) In general, the wear resistance decreased with the increase of testing temperature. But the decrease ranges were different for the composites with different silicon contents. The friction coefficient changed regularly with the silicon content.

(3) As the silicon particle content increased, the dominative wear mechanism would change from a relatively severe regime of plastic deformation accompanied by adhesion wear to a mild regime of smear, then to a very severe regime of severe plastic deformation induced wear, and finally again to a relative mild regime of smear accompanied by abrasive wear.

(4) As the testing temperature elevated, the wear mechanism would change from a mild regime of smear accompanied by abrasive wear to a severe regime of plastic deformation accompanied by adhesion wear.

References


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