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The effect of composition segregation on the friction and wear properties of ZA48 alloy in dry sliding condition

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Abstract In this study, the effect of composition segregation on the wear resistance of high aluminum zinc-based alloy is investigated. The test results show that the improving wear resistance is due to a combined action of α and η phase. The rich solid solution of $\alpha-$Al has higher strength and load bearing capability than of η phase. Under the action of the sliding friction, the hard α phase was protruded from matrix and acted as a loading phase. The η phase helped to act as a type of natural lubricant in sliding wear situations. Meanwhile, the iron transferred from the steel ring to block and forced to the recess continuously, which forms a thin protective film at the contact surface, then the load bearing capability of the test alloy would be improved.

Introduction

Zinc-based alloys have been used to a number of engineering and particular tribological applications for many years because of their low density, excellent cast ability, fluidity, lower energy requirement for shaping and superior wear properties [1–3]. It has been established that the mono-eutectoid zinc-based alloys have higher strength and wear resistance than either eutectic or eutectoid alloys. Though some alloys such as ZA27, ZA35, and ZA40 containing 27, 35, and 40% Al, respectively, have good wear resistance under heavy loads and poor lubrication conditions [4–7]. But, these alloys have lower elongation and tendency toward casting defects such as composition segregation and underside shrinkage. Some extensive research results have shown that the high aluminum zinc-based alloys have the best mechanical properties and tribological performance. However, the composition segregation also increased with increasing the Al contents, and the effect of composition segregation on tribological properties of these alloys has not been investigated. The purpose of this study is to investigate the effect of composition segregation on friction and wear properties of the ZA48 alloy in dry sliding condition.

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Experimental procedure

Material preparation

In present study, the chemical composition of the zinc-based alloy with 48 wt% aluminum content is shown in Table 1. The zinc-based alloy was prepared firstly by melting at about 610 °C and casting into a steel mold which had been preheated at 90 °C. In view of the heating characteristics of resistance furnace, the Zn-rich liquid phase could flow toward the bottom, while the Al-rich primary particles moved toward the top due to the difference on density between two phases. It caused the aluminum content of the tip lower than of top [2]. Therefore, the best way to investigate the effect of composition segregation on the wear property of ZA48 alloy is to remove the samples from different regions along the longitudinal

Table 1 Chemical composition of ZA-48 alloy in wt%

Al (%)	Mg (%)	Cu (%)	Zn
46–48	0.01–0.03	1–3	Balance

direction of the ingot. The tested samples near both the terminals are shown in Fig. 1.

Some samples were prepared using standard metallographic techniques and etched in 5% Nital, and examined by a JSM-6700F scanning electron microscope (SEM).

Friction and wear tests

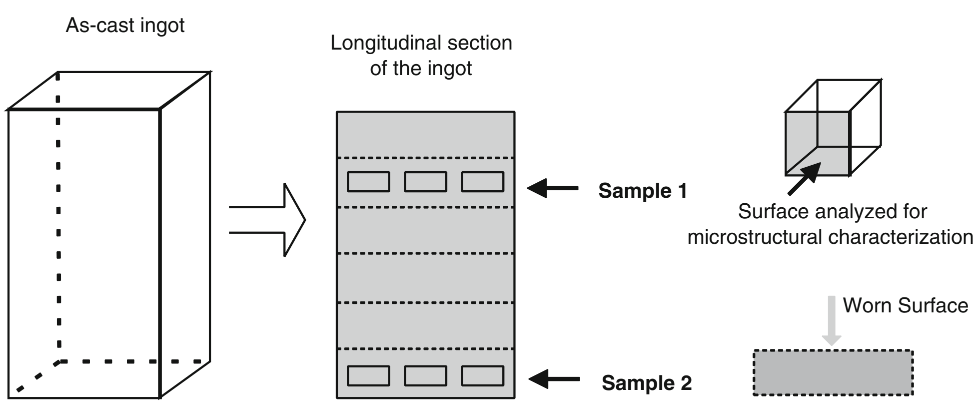
The friction and wear tests were conducted on a conforming block-on-ring type test machine. A schematic diagram of the tester is shown in Fig. 2a. The machine consists of a narrow rotating disk held vertically by the shaft, an edge-mounted block (specimen) and its mounting system, a loading system, and force and temperature measuring systems. A 45 Cr steel disk of diameter 160 mm was used as a counter partner. Samples were fabricated from the test alloy casting and machined with a 160 ± 0.01 mm diameter cutter from the end of sample so that the curved surface could conform exactly to the edge of the disk. The shape and dimensions of the sample are given in Fig. 2b. Friction and wear tests were performed under different pressures (20–100 N in step of 20 N) and at the sliding speeds of 0.5 ms^{-1}. The friction force was determined by using a load cell and the friction coefficient of the samples was calculated by dividing the friction force by the normal load. Each wear sample was ultrasonically cleaned and weighed before wear test using a balance with an accuracy of 0.01 mg. After wear test, each sample of the alloy was weighed and the mass loss due to wear was determined. The worn surfaces of the wear samples were examined using SEM.

Results

Weight loss

Figure 3 is a relationship between the weight loss of the materials and the applied loads of 20–100 N under a sliding speed of 0.5 m/s. The results showed that the weight loss of ZA48 alloy increased with the increase in applied loads. It can be considered that it is quite natural for the

Fig. 1 Samples for microstructure observation and wear test



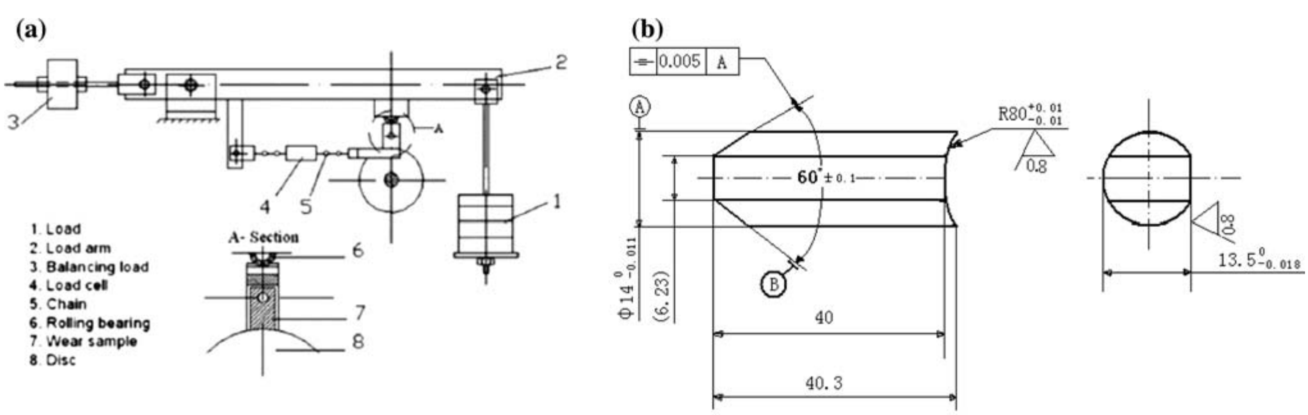


Fig. 2 **a** Schematic diagram of the wear tester and **b** technical drawing of the wear sample

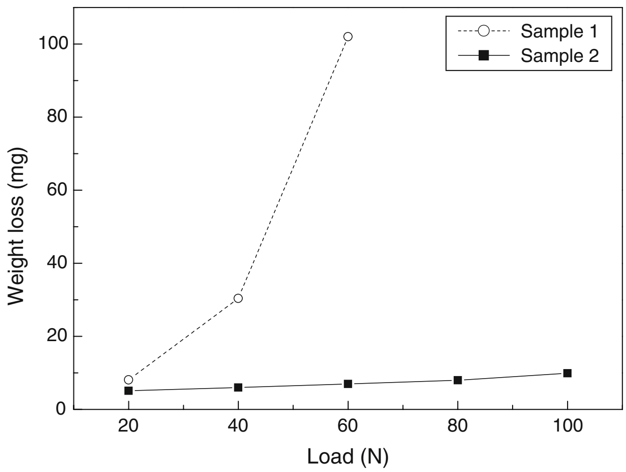


Fig. 3 Graph of weight loss vs. applied loads

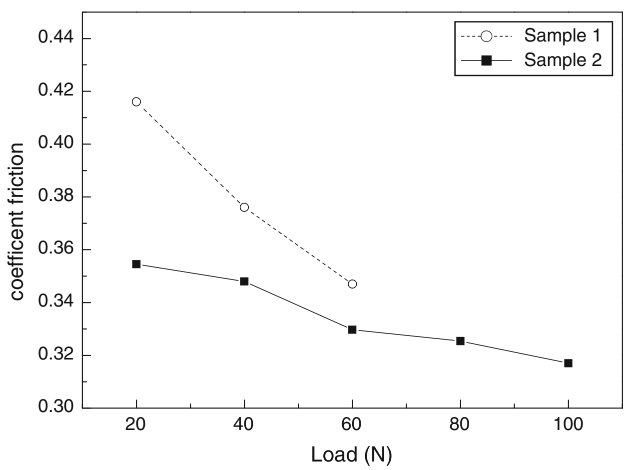


Fig. 4 Graph of coefficient friction vs. applied loads

wear rate to increase with load. However, different results were obtained in ZA48 alloy as shown in Fig. 3. For sample 1, the weight loss was higher than of sample 2, and there exists a transition from mild to severe at a load of 60 N. While the transition loads for sample 2 were much higher than that of the sample 1, the weight loss is still low even at a load of 100 N.

Frictional coefficient

Friction coefficient reflects the change of roughness of the alloy surface. Figure 4 shows the frictional coefficient of the test alloys at different loads. The results show that the frictional coefficient of ZA48 alloy was 0.3–0.4, and the frictional coefficient decreased with the increase of the load. The contact surface between metals during friction is usually in an elastoplastic state and the true contact area is non-linear to the applied load. This results in a decrease in the coefficient of the friction with increasing applied loads [8]. However, sample 2 showed lower frictional coefficient appreciably than those of sample 1, which reflects the lower roughness of sample 2 alloy surfaces than of sample 1. It might be a reason to cause the severe wear of sample 1.

Microstructure

Figure 5a–c showed the microstructure of the test alloy. The higher magnification microstructure of the ZA48 alloy is shown in Fig. 5a. It can be seen that the as-cast ZA48 alloys presented a primary α-dendrites structure surrounded by eutectoid ($\alpha + \eta$) along with the particles of metastable ε phase (Fig. 5a, regions marked A, B, and C, respectively). Comparative researches on microstructure of the sample 1 and sample 2 are shown in Fig. 5b and c. The more primary α-dendrites have been seen in sample 1.

The quantitative analysis results are shown in Fig. 6. It is a graph of the weight percentage of the elements investigated using energy dispersive spectrometer (EDS). The results showed that the Al contents of sample 1 increases by more 10% than of sample 2. Due to the high aluminum contents, the solidified dentritic grains may be interconnected rather promptly along certain fast growing directions, and the residual isolated each other into large

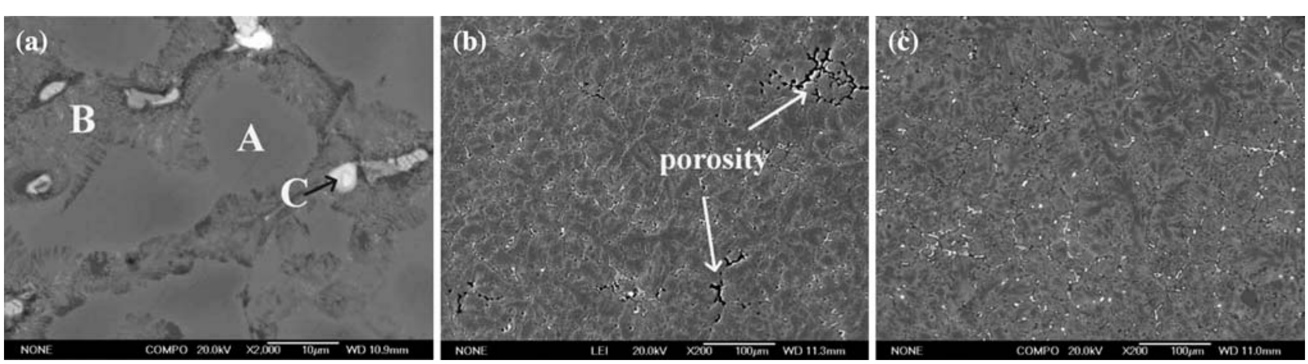


Fig. 5 The microstructure of the test alloys, **a** high magnification SEM microstructure of ZA48 alloy, **b** sample 1 and **c** sample 2 in a low magnification SEM

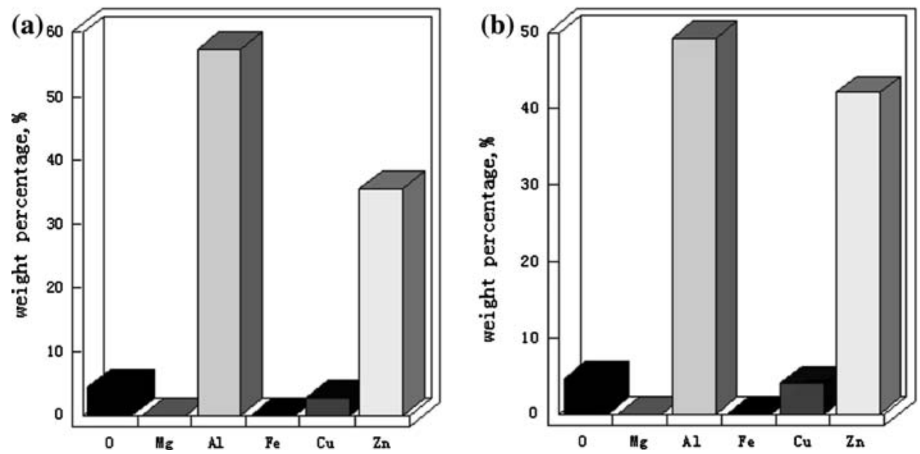


Fig. 6 Graph of the quantitative analysis results: **a** Sample 1 and **b** Sample 2

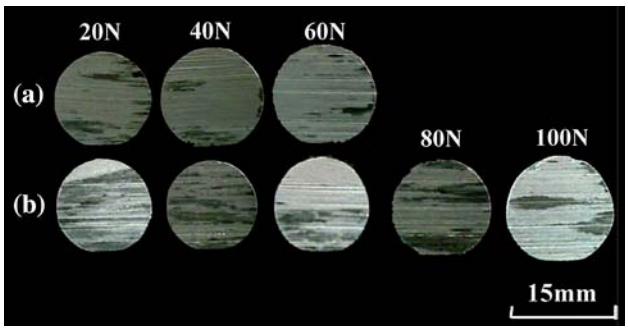


Fig. 7 Macrograph features of the worn surface: **a** Sample 1 and **b** Sample 2

pools in middle or end solidified period. Therefore, more serious porosities will be formed in sample 1 as shown in Fig. 5b. It might be another reason causing the severe wear of the sample 1.

Worn surface

Figure 7 shows macrograph features of the worn surface morphology of the test specimens at different applied loads. EDS examination as shown in Fig. 8 shows that the black material in worn surface was Fe and O, which may be iron oxide. The iron oxide is located in worn surface unevenly and decreases with the increasing applied loads.

For sample 1, less iron oxide has been seen on worn surface and vanished almost completely at a load of 60 N. More iron oxides have been seen in sample 2 and the iron oxide still exists even at the load of 100 N. It might be the primary reason causing the severe wear of the sample 1. The SEM examination on worn surface of the tested alloys has been presented in Fig. 9. For brevity and convenience, the micrographs of the test alloys at only the 40 N load have been presented. However, the explanation is provided for the composites with other test loads as well. Observation on worn surface of sample 1 is shown in Fig. 9a. The locally damaged and even fractured spots are observed. These are indications of severe deformation and fracture resulting in a high wear rate. The sample 2 shows a mixed abrasion-plastic deformation mechanism as an evident in Fig. 9b. A layer of black iron oxide is located in recess unevenly which induced the low weight loss of the sample 2.

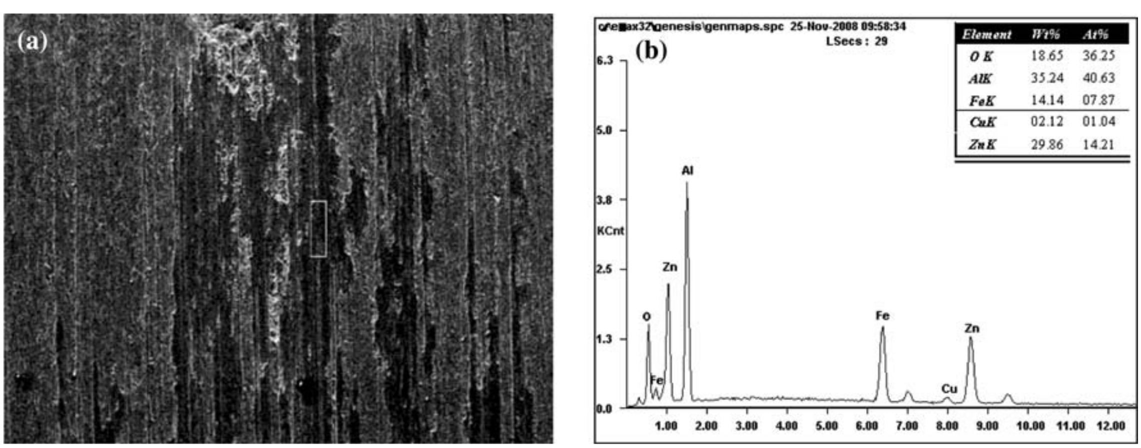


Fig. 8 **a** SEM image of the black material formed in the worn surfaces, **b** EDS analysis of the black material

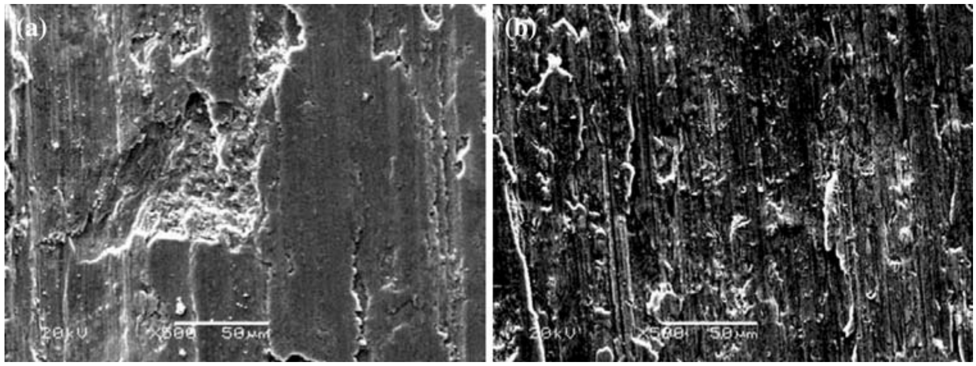


Fig. 9 SEM showing the worn surfaces of the test alloys at load of 40 N: **a** Sample 1 and **b** Sample 2

Discussion

Microstructure shows that the ZA48 alloy is comprised basically of the α and η phase. In view of the heating characteristics of resistance furnace, the Zn-rich liquid phase could flow toward the bottom, while the Al-rich primary particles moved toward the top due to the difference on density between two phases. It caused the aluminum contents of the bottom lower than of the top and the severe segregation is formed. The α−Al rich solid solution has higher strength and load bearing capability than of η because of the higher melting point of Al (than of Zn) and its (fcc) structure. Under the action of the sliding friction, the soft η phase prior to the α phase was removed and the hard α phases were protruded from matrix and acted as a loading phase. Extensive zinc transfer occurred and helped to act as a natural lubricant in sliding wear situations wherein the smearing behavior is facilitated and a lubricating film on mating surfaces is formed. Meanwhile, the iron transferred from the steel ring to block and forced to recess continuously during sliding wear, which forms a thin film at the contact surface between the composite and the counter face as shown in Fig. 7. It is equivalent to a number of reinforced particulates added to the ZA48 alloy, and its load bearing capability would be improved. In other words, the improving wear resistance is the combined action of α and η phase. The excess aluminum may lead to the advantageous effect of η phase on wear property. Also less iron transfer happened as shown in Fig. 7. It induced the decrease of the load bearing capability. Extrapolation of the test results shows that the proportion of α and η phase has an optimum range. The wear resistance was improved when the α−Al rich solid solution added up to a specific quantity. However, the specific range is not fully understood and need further work.

Conclusion

(1) The as-cast ZA48 alloys basically presented a primary α-dendrites structure, and it is surrounded by eutectoid ($\alpha + \eta$). The severe composition segregation is formed due to the high aluminum contents.
(2) The composition segregation has a great effect on wear resistance of the ZA48 alloy.
(3) The superior wear properties are the combined action of α and η phase. The soft η phase was removed and acted as a natural lubricant in sliding wear situations. The hard α phases were protruded from matrix and acted as loading phase. Meanwhile, the iron transferred from the steel ring to block and forced to the recess continuously during sliding wear, which forms a thin protective film at the contact surface, its load bearing capability would be improved.

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