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Sliding wear and friction behavior of ZA-27 alloy reinforced by Mn-containing intermetallic compounds①

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[Abstract] A ZA-27 alloy reinforced with Mn-containing intermetallic compounds was prepared and its tribological behaviors were investigated. By adding Mn, RE, Ti and B into ZA-27 alloy, the test alloy (ZMJ) was fabricated by sand casting. Microstructural analysis shows that considerable amount of Mn-containing intermetallic compounds such as Al_5MnZn, $Al_9(MnZn)_2$ and $Al_{65}Mn(RE)_6Ti_4Zn_{36}$ are formed. Compared to ZA-27, ZMJ shows better wear resistance, lower friction coefficient and lower temperature rise of worn surface under lubricated sliding condition. ZMJ also shows the lowest steady friction coefficient under dry friction condition. The wear resistance improvement of ZMJ is mainly attributed to the high hardness and good dispersion of these Mn-containing intermetallic compounds. It is indicated that the intermetallic compounds play a dominant role in reducing the sever adhesive and abrasive wear of the ZA-27 alloy.

[Key words] ZA-27 alloy; intermetallic compounds; sliding wear; friction
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1 INTRODUCTION

Since the Second World War, Zn-Al alloys have been successfully developed to replace lead bronzes in bearing and bushings[1~4]. Compared to lead bronze, ZA alloys offer a combination of high strength, low density and low cost. However, when sliding under a heavy load, the wear resistance of ZA-27 alloy turns worse due to the sever deformation, ploughing, adhesion and temperature rise of the worn surface[5]. Many efforts have been made to improve the anti-friction, wear-resisting and load-bearing ability of ZA-27 so as to expand its industrial application. Investigations show that hard phases can be formed by adding modifying elements such as manganese, silicon and RE (rare earths) into ZA-27. These modified zinc alloys show higher wear resistance[6~8]. Some zinc-based composites were developed to enhance the load-bearing ability of ZA-27. Based on the chemical composition of ZA-27 and adding Mn, RE, Ti and B as modifying elements, a novel high-strength, high wear-resisting zinc alloy named ZMJ has been developed in our previous research[9~11]. In this paper, the sliding wear and friction behavior of the alloy are further investigated and its wear mechanism is discussed.

2 EXPERIMENTAL

Zinc-based alloys with a chemical composition (mass fraction) of 26% ~ 29% Al, 2.0% ~ 2.5% Cu, 0.03% ~ 0.06% Mg and trace amount of Mn, RE(Ce ≥45%, 23% ~ 28% La, 17% Nd and 5% ~ 6% Pr), Ti and B were prepared by sand casting. High-melting-point elements were introduced in the form of master alloys with aluminum. Raw materials were melted at 650 ℃ in a graphite crucible. After degassing and removal of covering slag, the melted alloy was then poured into a sand mold, which was preheated to approximately 150 ℃ in open air. Samples for mechanical properties and tribological behavior tests were machined from as cast materials. ZA-27 and ZCuSn10P1(10.8% Sn, 0.27% P, balance Cu) were prepared for comparison.

The microstructure and worn surface of the zinc-alloy were examined by optical microscope and S-550 scanning electron microscope. Micro-constituents were measured by an EPM-810Q electron microprobe with wavelength dispersive spectroscopy (WDS) and a S-550 scanning electron microscope with an energy dispersive spectroscopy (EDS). The micro-hardness was measured by a model 71 micro-hardness tester. Brinell hardness was measured by a HDI-1875 hardness tester. Mechanical properties at room and elevated temperature were tested on a WD-10A electronic tensile testing machine and a WJ-10A mechanical tensile testing machine, respectively. A MPX-200 pin-on-disk tribometer was used to measure the friction coefficient of the alloy samples under different loads and lubricating conditions. Disks were made of the test alloys, the pins were made of heat-treated ASTM 1045 steel with a hardness of HRC 48. Nominal specific pressures used were 9.98, and 29.95 MPa and

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the sliding speed was 0.504 m/s. No. 20 lubrication oil was used as the lubricant. Dry friction coefficient was measured at the same load and speed without any lubricant. A bush bench tester was used to measure the wear rate and temperature rise of worn surface. The test materials were machined to bushes with an outer diameter of 58 mm, inner diameter of 40 mm and a thickness of 40 mm. The counterpart shafts were made of ASTM 1045 steel with an outer diameter of 40 mm. The wear test was conducted under an applied pressure of 7.84 MPa and sliding speed of 0.555 m/s. No. 803 lubricating grease was used as the lubricant and pumped onto the sliding surface once every 5 min. After sliding for 6.5 h, the temperature rise on worn surface was measured by a thermometer and the mass loss of test bush was measured by a 65A-3 electronic balance.

3 RESULTS AND DISCUSSION

3.1 Microstructures

Microstructures of the tested alloys were presented in Fig. 1. The microstructure of ZCuSn10P1 is characterized by α (Cu rich solid solution) dendrite with some (α+ δ+ Cu_3P) eutectoid and Cu_3P phase distributed in the inter-dendrite space. ZA-27 is characterized by α(Al rich solid solution) dendrite with some (α+ β) + (α+ β+ ε) eutectics and ε phases dispersed in the inter-dendrite region. For ZMJ, three kinds of Mn-containing intermetallic compounds such as Al_5MnZn, $Al_9(MnZn)_2$ and $Al_{65}Mn(RE)_6Ti_4Zn_{36}$ are formed due to the modification of Mn, Ti, and RE. The expressing formulas were determined by the constitution analysis of phases[10]. The intermetallic compounds are dispersed in the eutectic region and α dendrites. The morphologies of the Mn-containing intermetallic compounds vary from fine rods to irregular particulates.

By quantitative metallographical analysis, volume fractions of different phases in experimental zinc alloys were examined. The results are listed in Table 1. It can be found that the volume fraction of intermetallic compounds in ZMJ is higher than that in ZA-27 and the grain size of α phase in ZMJ is finer than that in ZA-27. Both phenomena can be seen clearly in Figs. 1(b) and (c).

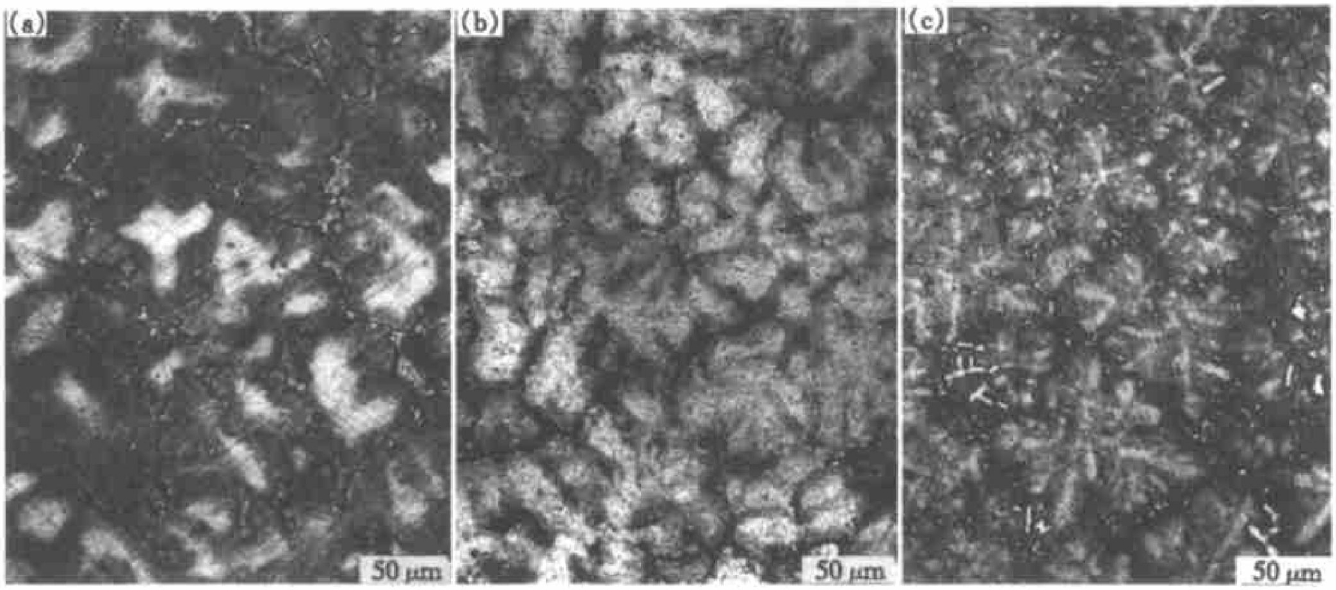

Fig. 1 Microstructures of tested alloys
(a) —ZCuSn10P1; (b) —ZA-27; (c) —ZMJ

Table 1 Microstructural characteristics of ZMJ, ZA-27 and ZCuSn10P1

Sample	Phases	Microhardness of phases(HV)	Volume fraction of phases/ %	Average size of phases/ μm
ZMJ	α dendrite	55.7~ 82.2	78.2	78
	α+ β and α+ β+ ε eutectics	49.1	7.0	
	ε ($CuZn_3$) phase	230.1		
	Al_5MnZn	616.8	14.8	18
	$Al_9(MnZn)_2$	560.9		
	$Al_{65}Mn(RE)_6Ti_4Zn_{36}$	380.8		
ZA-27	α dendrite	41.1~ 90.7	80.2	103
	α+ β and α+ β+ ε eutectics	27.5	12.8	
	ε ($CuZn_3$) phase	235.5	7.0	6

3. 2 Mechanical and wear-resisting properties

Table 2 lists some basic properties of ZMJ compared with those of ZCuSn10P1 and ZA-27. It is found that the elevated temperature strength and hardness of ZMJ are higher than those of ZA-27. Both zinc alloys have better or comparable mechanical properties below the temperature of 150 ℃, however, at the temperature of 200 ℃, ZCuSn10P1 has the best tensile strength. As zinc alloy has much lower melting point than bronze, it is reasonable that the elevated-temperature strength of zinc alloys samples is lower than that of ZCuSn10P1.

Results of bush bench test show that the wear rate of ZMJ is lower than that of ZA-27. After sliding with the steel shaft for 6. 5 h under the test condition, the wear volume of ZMJ bush is only 26. 5% of that of ZA-27 bush. The temperature rise of worn surface is a reflection of the frictional heat generated during sliding. The surface temperature rise of ZMJ bush was lower than that of ZA-27. It is indicated that the temperature rise of worn surface decreases with reducing wear rate. Low temperature rise is desired to maintain the mechanical and wear-resisting properties of the zinc alloys during wear process.

3. 3 Friction characteristics

Fig. 2 describes the friction behaviors of ZMJ, ZA-27 and ZCuSn10P1 at the sliding speed of 0. 504 m/s under oil lubricating condition. The friction coefficient of ZMJ is the lowest among the test alloys. Both zinc alloys show a steady and lower friction coefficient than ZCuSn10P1. When the nominal specific pressure is 9. 98 MPa, the friction characteristics of ZMJ is similar to that of ZA-27. When the nominal specific pressure is increased to 29. 98 MPa, the friction coefficients of tested alloys increase, the friction coefficient of ZMJ is lower than that of ZA-27. The decrease of friction coefficient in reinforced ZA-27 may be caused by the reduction of adhesion wear due to the intermetallic compounds in ZMJ.

Fig. 3 shows the friction behaviors of ZMJ, ZA-27 and ZCuSn10P1 under the nominal specific pressure of 9. 98 and 29. 95 MPa when sliding at the speed of 0. 504 m/s without any lubrication. When the nominal specific pressure is 9. 98 MPa, the friction coefficient of ZA-27 fluctuate dramatically with increasing sliding distance, which indicates that the worn surface of ZA-27 stuck to the steel and slipped away from it alternatively during sliding. When the applied pressure is increased to 29. 95 MPa, the friction coefficient of ZA-27 increases rapidly up to 0. 480 8 after a short sliding distance, then a seizuring took place. However, ZMJ shows the lowest stable dry friction coefficient during the sliding process, which indicates that the intermetallic compounds dispersed in it have prevented the alloy from severe adhering and seizureing, thus decreasing the friction coefficient of it.

Without the lubricating oil to carry away the frictional heat and form a separating film between the sample and the counterpart, ZA-27 becomes very easy

Table 2 Results on mechanical and wear-resisting properties of ZMJ, ZA-27 and ZCuSn10P1

Alloy	Tensile strength at 250 ℃/MPa	Brinell hardness	Tensile strength at 150 ℃/MPa	Tensile strength at 200 ℃/MPa	Wear volume/mm^3	Temperature rise of worn surface/ ℃
ZMJ	376	135	299	177	2. 33	46. 75
ZA-27	392	112	231	159	8. 8	60. 73
ZCuSn10P1	310	90	231	200	—	—

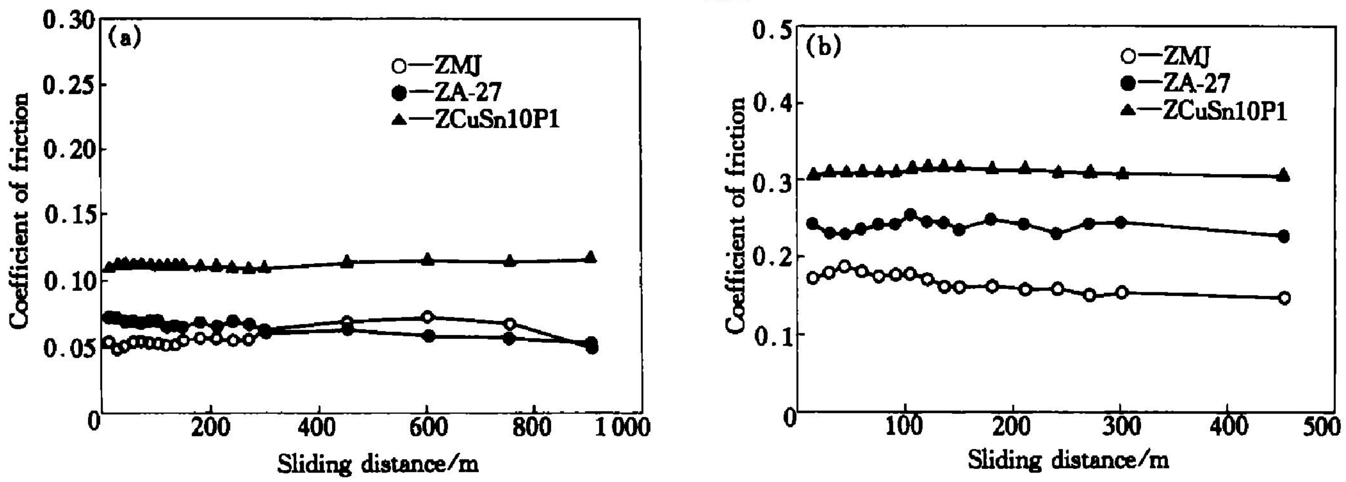

Fig. 2 Friction coefficient of ZMJ, ZA-27 and ZCuSn10P1 at sliding speed of 0. 504 m/s under lubricating condition
(a) —Nominal specific pressure= 9. 98 MPa; (b) —Nominal specific pressure= 29. 95 MPa

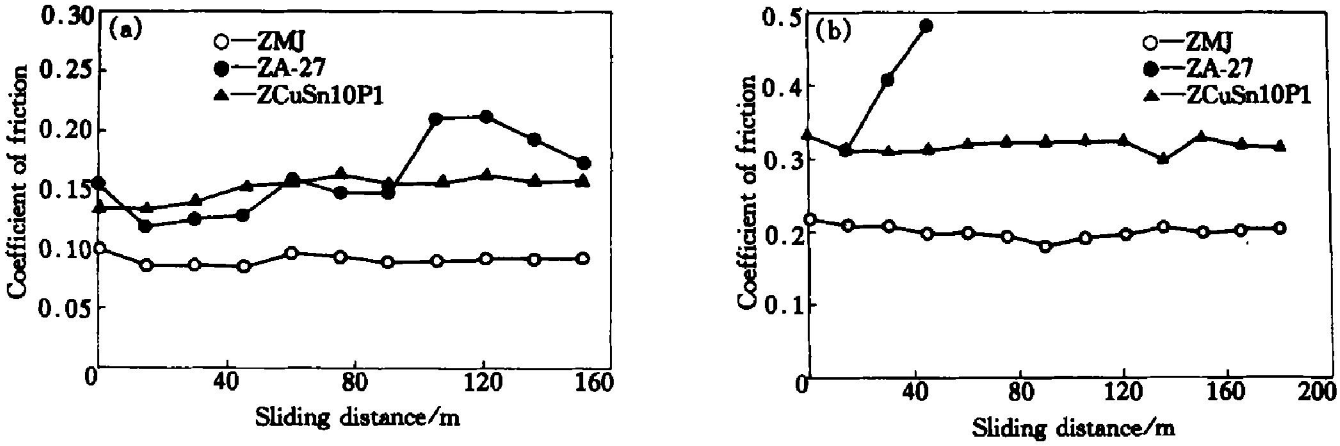

Fig. 3 Friction coefficients of ZMJ, ZA-27 and ZCuSn10P1 at sliding speed of 0.504 m/s under dry friction condition
(a) —Nominal specific pressure= 9.98 MPa; (b) —Nominal specific pressure= 29.95 MPa

to adhere with steel and lose its anti-friction ability under dry sliding condition. Compared with ZA-27, ZMJ can provide good anti-friction ability under both dry and lubricating conditions.

3.4 Discussion

From Table 2, it can be concluded that the wear rate of ZMJ is lower than that of ZA-27 and as well ZCuSn10P1 under the test condition, which can be attributed to the better mechanical property of ZMJ, especially its higher hardness.

According to Archard Equation[12]

$$Q = (B \cdot W)/H \tag{1}$$

where Q is the wear rate, W is perpendicular load applied on the worn surface, H is the hardness of worn material; the wear rate decreases with the increase of hardness of the material. Since the hardness of ZMJ is the highest among the test alloys, it shows the best wear resistance in wear test.

Frictional heat may be generated during the wear process and the temperature of the worn alloy will increase, especially at the contacting zone between test alloys and counterparts. Therefore, the sample becomes soft and its load-bearing ability decreases. So the wear resistance has a great dependence on elevated temperature mechanical properties. From Table 2, it can be found that the elevated temperature strength of ZMJ is higher than that of ZA-27. The improvement of elevated temperature strength is beneficial to the wear resistance of the tested alloy. It can be seen clearly from Fig. 1 (c) that there are many fine intermetallic phases dispersed on the matrix, which will improve the elevated-temperature strength of the alloy by dispersion strengthening and grain boundary strengthening.

The wear mechanism changes with the microstructure characteristics. It can be seen in Figs. 1 (a) and (b) that ZA-27 and ZCuSn10P1 have lower volume fractions of hard phases. Investigation shows that both of them show obvious abrasive, adhesive and surface fatigue wear characteristics[9]. Due to the lack of hard phases distributed on the metal matrix, soft metal matrixes are ploughed heavily by the hard phases in steel counterface. The concentration of load and frictional heat on the contacting spots may lead to cold-welding of tested material and steel. For ZMJ, it was found that adhesive wear has been hindered and mild abrasion is its major wear mechanism[9]. Microstructure shown in Fig. 1(c) and analysis in Table 1 show that the volume fraction of hard phases in ZMJ is higher than that in ZA-27, the hard phases are dispersed in both the α dendrite and the interdendite eutectics. Furthermore, $CuZn_3$ is the only hard phase in ZA-27, while there are three Mn-containing intermetallic compounds in ZMJ besides $CuZn_3$, whose microhardness are much higher than that of $CuZn_3$. The hard phase in worn surface can reduce the direct contact between soft metal matrix and steel counterpart, thus preventing the counterparts from severe adhering during wearing process. The hard phases also play an important role in bearing load from the counterpart therefore decrease the abrasion of the soft metal matrix. As there are more and harder reinforcing particles well dispersed in ZMJ compared with ZA-27, adhesive and abrasive wear in the alloy have been reduced. That's why ZMJ has the slowest wear rate and the lowest friction coefficient under the tested condition compared to the unmodified ZA-27.

4 CONCLUSIONS

By adding Mn, RE, Ti and B into ZA-27 alloy, more and harder intermetallic compounds were formed. Compared with ZA-27, ZMJ shows better anti-friction and wear-resisting ability, which is attributed to the microstructure modification. The intermetallic compounds in ZMJ play an important role in improving its tribological performance.

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