Tribological Characteristics of Submicron SiC(p)-GR(p)/Zn-35Al-1Mg Composites in Semisolidification Casting process

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Abstract. Uniform SiC(p)-GR(p)/Zn-35Al-1Mg composites were prepared by powder pressing and semisolidification stirring-casting process by adding submicron silicon carbide and graphite reinforcement particles in an aluminum-zinc alloy matrix. Micro Vickers hardness and microstructures of the novel composites were studied, and their wear properties and wear temperature were measured for different load and friction conditions. The results show that silicon carbide and graphite particles homogeneously mix in the matrix, while contained silicon carbide particles improve the matrix hardness to 8.4%, graphite improves the matrix hardness to 16.8%, but two of them, combined, reduce the matrix hardness to 7.6%; the rate of temperature rise of the zinc-aluminum matrix alloy is the highest than the other three composites and is up to 48.5° C/s at 1.69MPa. At 0.56MPa and sliding 26.4km, the graphite composite anti-wear effect is optimal, while at 1.13MPa, the wear resistance of silicon carbide and graphite compound particles is the best; in the other case of only silicon carbide particles, the wear resistance is increased to 35% at 1.69MPa and 26.4km, and its anti-wear effects are excellent.

1. Introduction

Casting Zn-Al based alloy is widely used in Mechanical engineering for its favorable processing, mechanical, and wear-resisting properties, and it has been drawing attention from manufacturers and researchers because of its wide application on bearing bush, piston and sliding blocks[1-3]. However, the defects represented by the low hardness and unsatisfying under heavy load and high temperature have been limiting its range of application[4]. But with the addition of SiC and graphite and other particles enforcement into Zn-Al matrix alloy, the wear-resistance and friction decreasing properties can be acquired for the matrix alloy[5]. SiC as a hard phase in Zn-Al matrix alloy can improve the wearproperty effectively, while graphite being soft phase, can increase friction-resisting property as
well. The wear-resistance of the key component-bearing bush, which is damageable as a part of engine, has to be improved as much as possible while ensuring the safety of its spouse friction pair[6,7].

The research of improving wearresistance on matrix by adding SiC and graphite particles simultaneously is rarely reported, so this work involves the preparation of Zn-Al matrix composites containing SiC and graphite particles, the study of its wear characteristics and wear temperature principles under different load and wear distance, thus providing important parameters for the further application of new type Zn-Al matrix composites. Therefore, as a kind of light weight material, the new type casting SiC\textsubscript{(p)}+GR\textsubscript{(p)}/Zn-35Al-1Mg composites used as transmission components in mechanical engineering will have a wider range of application in the future.

2. Materials and experimental

Zn-35Al-1Mg matrix alloy was prepared by casting using pure Zn(99.9%), pure Al(99.9%) and pure Mg(99.9%) allocated in portion. The middle composites were produced by Aluminium particles with the particle size of 300~400 meshes, SiC particles and GR particles with the particle size of about 5000 meshes. First of all, Al, SiC and Gr particles put into the QM3SP4L planetary ball mill were ball milled for 8 hours at speed of 400rpm. After that, the mixed powder were allocated in rectangular forming mould, and then completely compressed on YES-2000 Digital hydraulic pressure machine, which the middle composites were produced after the finalization of the process. Second, Al ingots were placed in steel crucible with ZnO painted in its inner surface, which were put into SG2-3-10 resistance furnace with automatic temperature control system to be heated at 720°C and kept for 8 minutes. Then Ar was conducted as protective atmosphere to the furnace while added Zn, Mg ingots and 10%SiC\textsubscript{(p)}/Al, 10%GR\textsubscript{(p)}/Al and 5%SiC\textsubscript{(p)}+5%GR\textsubscript{(p)}/Al middle composites together wrapped to the bottom of Al liquids, after the addition for 5 mins, the mixed melting liquids were stirred at 500rpm and kept the furnace temperature cooled to 600°C for 10 minutes until they were mixed well. Finally, experimental ingots were prepared in \( \Phi 15 \text{mm} \times 50 \text{mm} \) metal mould.

As-casting composites were processed to \( \Phi 8 \text{mm} \) specimens, then they were subjected to heat treatment, which was performed by solid-solution at 500°C for 4 hours, aged naturally for 36hours. After heat treatment, the friction wear properties of the composites at the friction distance of 0.45km, 2.2km, 6.6km, 13.2km, 26.4km were measured under the loads of 0.56MPa, 1.13MPa and 1.69MPa on friction wear testing machine. In the meantime, the wear temperatures of materials under different conditions against friction distance were recorded using TP1000 temperature recorder.

Wear sections were embedded in conductive resin using ZXQ-2 automatic mosaic machine, then the microstructural examinations from embedded ingots were measured by ZEISS metallographic microscope and PHILIPXL30TMP SEM equipments with standard metallographic techniques, that as rough-grinding, fine-grinding and polishing, then they were etched in a beaker with mixed etching solution for 4 minutes. The mixed etching solution contained two hydrofluoric acid, three muriatic acid, four nitric acid and one hundred ninety distilled water, which was placed in a constant temperature mixing crucible. After the etching, the specimens were dried using hot air for following observation.
3. Results and discussion

The curve showing mass loss of different composites with sliding distance is given in Fig. 1. In the view of these results, SiC\(_p\) the single addition exhibited better effect of improving wear resistance of matrix alloy under heavy load than SiC\(_p\)+GR\(_p\) composites addition or GR\(_p\) the single addition does. What’s more, according to the appearance of wear surface and wear temperature, GR\(_p\) exhibited softness and possessed favorable lubricity and it was favorable for decreasing wear mass loss under lower load; on the contrary, a moderate amount of homogeneously dispersed SiC\(_p\) exhibited high hardness, strong carrying capacity under heavy load, which was beneficial for decreasing wear mass loss of materials; besides, they also possessed small thermal expansion index and high thermal conductivity, etc. that enabled SiC\(_p\) to disperse the high heat on friction surface yielded by friction under heavy load, therefore protecting the matrix material from being further damaged.

![Fig. 1 The relationship between wear mass and sliding distance of the composites: (a) 0.56MPa, (b) 1.13MPa, (c) 1.69MPa](image)

The appearance of the wear stripping films of composites under load the 1.69MPa is shown in Fig. 2. It can be seen that four composites as-cast Zn-35Al-2Mg, composites single added SiC\(_p\), composites single added GR\(_p\) and composites added SiC\(_p\)+GR\(_p\) composite all yielded many striping films and these films accumulated on the margin of the wear section of wear specimens. As is shown in Fig. 2(b), composites single added SiC\(_p\), exhibited a different wear surface compared with three other composites, which can be explained by the fact that homogeneously dispersed SiC\(_p\) enabled partial Zn-Al solid solution to conduct and disperse the heat in time and that Zn-Al alloy remaining on the surface, which was oxygenized and melted, prompted the surface to form into paste.
Fig. 2 The wear morphology of composites in frictional contact pressure 1.69 MPa: (a) Zn-35Al-1Mg, (b) 1SiC$_{(p)}$+, (c) 1Gr$_{(p)}$+, (c) 0.5SiC$_{(p)}$+0.5Gr$_{(p)}$+

It can be seen from Fig. 3 that the friction started, the maximum temperature increasing rate of four composites in different frictional condition, which was calculated to 48.5°C/s; similarly, when the wear ended, the maximum temperature decreasing rates of these four composites can also be calculated as 51.4°C/s. Besides, it can be seen from Fig. 3 that during friction wear process, composites added graphite particles, SiC particles or these two combined exhibited different wear temperature change. Specifically, the addition of SiC and graphite under load of 0.56 MPa can yield a lower wear temperature after wearing at a sliding distance of 1.32 km compared with composites single added SiC, single added graphite or the matrix alloy; Also, not surprisingly, the maximum wear temperature under load of 1.13 MPa was slightly higher than the wear temperature under the load of 0.56 MPa, for the load of 0.56 MPa, the maximum wear temperature was produced by the direct wear of Zn-Al matrix materials and can rise to 230°C approximately during wear, while for the load of 1.13 MPa, the maximum wear temperature was produced when single adding SiC particles and can rise to approximately 260°C during wear, and wear temperature of composites containing SiC particles also rose with the increase of the load. However, composites single added graphite all displayed lower wear temperature under different loads, because the distribution of graphite particles enabled the composites to exhibit good friction reduction property on wear surface after it was stripped away from worn matrix alloy under low load; however, the wear temperature decreasing effect was not evident for the composites added SiC and graphite mixed particles compared with composites single added SiC particles or single graphite particles.
Fig. 3 The relationship between wear temperature and sliding distance of the composites: (a) 0.56MPa, (b) 1.13MPa, (c) 1.69MPa

The microstructure of new type SiC\textsubscript{(p)}-GR\textsubscript{(p)}/Zn-35Al-2Mg composites wear surface under load of 1.69MPa was shown in Fig. 4. It is known that the parent phase in the structure of composites was dendritic Zn-Al solid solution, consisting of primary α-phase, and α+β mixed eutectoid phase; and the white dendritic α-phase was solid solution formed by Zn melting into Al; η-phase was the solid solution formed by Al melting into Zn, around the margin of dendrite of which, a small amount of Mg-Zn compound was distributed. It can be seen in Fig. 4 that the silver gray flaky particles appearing in Fig. 4(b)(d) were SiC particles, while the black particles were graphite particles. Besides, the solid solution in Fig. 4(a)(b)(c)(d) exhibited different appearances, for example, it can be seen from Fig. 4(a) that dendrites of Zn-Al solid solutions were slender and long; dendrites of Zn-Al solid solution; the Fig. 4(b), however, were thick, short and small in Fig. 4(b) affected SiC\textsubscript{(p)} particle; Fig. 4(c) showed a decreasing amount of dendrites, which existed in the form of tiny particles dispersively distributed; as was shown in Fig. 4(d), the addition of SiC\textsubscript{(p)} and GR\textsubscript{(p)} composite particles transformed dendritic Zn-Al solid solution into tiny petal clusters dispersively distributed. As a result of the description of the microstructural appearance above, it is known that SiC\textsubscript{(p)} and GR\textsubscript{(p)} particles did have some influences on the microstructure of high Zn-Al matrix alloy, more specifically, dendrites of Zn-Al solid solutions thickened after the introduction of SiC\textsubscript{(p)} and GR\textsubscript{(p)} particles, with previously slender dendrites transformed into short, thick petal shape and the blunting of sharp angles of former slender dendrites.
Fig. 4 The microstructure of worn surface in different composites during the same condition: (a) Zn-35Al-1Mg, (b) 1SiC\(_p\)+, (c) 1Gr\(_p\)+, (d) 0.5SiC\(_p\)+0.5Gr\(_p\)+

The hardness of samples was measured by HV-1000/HV-1000A Vickers microhardness tester with 1.961N set for the test stress series and hardness range was set within HV0.2. During the test, the microhardness of 7 points along the radial direction were measured every 0.1mm. And the center of the specimens was chosen as the benchmark for the determination of these 7 points. The average of hardness of them were determined as final Vickers microhardness value. The HV of Zn-35Al-2Mg, 3%SiC\(_p\)/Zn-35Al-2Mg, 3%Gr\(_p\)/Zn-35Al-2Mg and 1.5%SiC\(_p\)+1.5%Gr\(_p\)/Zn-35Al-2Mg was 131, 142, 109, 121 separately. It can be seen from the results that SiC\(_p\) increased the microhardness by 8.4%, on the contrary, the hardness of composites added Gr\(_p\) decreased by 16.8% compared with matrix material, however the introduction of SiC\(_p\) Gr\(_p\) caused microhardness to decrease sharply, which was 7.6% less than the matrix alloy.

The friction surface of materials and its spouse mill during friction process were softened due to sharp temperature increase, thus diminishing the deformation resistance of the materials and the mill. So during the wear under the continuous effect of friction shearing strength, the wear surface broke apart from the matrix and peeled off, which also took away high heat on wear surface thus cooling the wear surface. Then temperature would rise again due to the friction until reaching the stripping temperature and then the stripping films would take away the heat again, therefore the temperature during the process would circulate in this way until reaching stability. When there was relative sliding between composites and its spouse friction steel plate, the friction surface temperature rose and large plastic deformation occurred because of the friction on contact surface caused by outer load, the metals on the surface exhibited partial gelling effect under thermal compressing influence and therefore would be broken by molecular stress during the following relative sliding, during which the
metal fragments were dragged away from the components thus causing abrasion on component surface, so this was the reason why stripping films formed on wear surface in the experiment and it also determined that it was the gelling wear form that distinguished the wear of composites.

It can be seen from Fig.4 that SiC\(^{(p)}\) and GR\(^{(p)}\) were dispersively distributed in the form of small particles in the matrix. The reciprocal compression between friction parts after the start of friction made SiC\(^{(p)}\) and GR\(^{(p)}\) on contact surface behave in different forms, for SiC\(^{(p)}\), it was top distribution, the actual contact area was small, and plastic deformation of matrix would occur once under large contact stress effect. However, differently, GR\(^{(p)}\) stripped away from matrix directly fell into friction contact area causing lubrication and friction-reducing effects, which effectively improved the wear-resisting property under heavy load but did not exhibit apparent effects under the heavy load. The reason why GR\(^{(p)}\) failed to play an important role under heavy load was that the large stress between contact surfaces forced material to go through both the plastic deformation and creep deformation, which in turn decreased deformation resistance of material sharply and stripped away Zn-Al solid solutions and graphite particles possessing soft phase from matrix alloy during friction, therefore leading to the failure of the GR\(^{(p)}\) friction-resisting effect. However, in the meantime the SiC\(^{(p)}\) with favorable microhardness began to substitute GR\(^{(p)}\) and it also exhibited favorable heat conductivity, which lately can effectively prevent materials from going through creep deformation caused by increasing wear temperature; what’s more, according to the comparison of Vickers hardness, the white dendritic phase possessed higher hardness than phase solid solutions formed by Al melting into Zn. Besides, it is known that for phase, Zn can form infinite solid solution in Zn, while for phase, Al can only form finite solid solution in Zn, therefore according to solid solution reinforcement effects, when α and η phase coexist, the existence of more phase can lead to higher wear-resistance. Moreover, the coexistence of α and η phase transformed brittle dendritic structure (especially fragile under continuous high temperature shear stress) to petal shaped structure, which blunted the sharpness of dendrites thus positively hindering the breakage of them, sobetter wear-resisting property was acquired by adding both SiC\(^{(p)}\) and GR\(^{(p)}\). Finally, the small amount of Mg in matrix alloy improved the creep strength of matrix and led to effective soaking of SiC particles into matrix, which in turn increased the dislocation density of grains therefore improving the wear-resistance of materials effectively.

4. Conclusions

1. Zn-Al matrix alloy composites with reinforcement particles mixed homogeneously can be produced by stirring casting process after powder-compacting, the microhardness increase of composites compared with the matrix differed when adding different particles, which was 8.4% for the single addition of SiC and 16.8% for graphite particles, however, the microhardness exhibited a decrease by 7.6% when adding mixed SiC and graphite particles.

2. The maximum temperature rising rate of four composites was 48.5°C/s when the wear began, while the maximum temperature decreasing rate of these composites was 51.4°C/s in the end of the wear, the wear temperature change of materials single added SiC particles under heavy was not apparent with the increase of wear time.

3. The wear mass loss decreases compared with matrix alloy differed between different composites under low load at a sliding distance of 26.4km, among which, the highest was 18% produced by composites added graphite particles decreasing, followed by 12% decrease exhibited by adding graphite and SiC particles, however, the addition of SiC single did not show an evident effect.
4. Under the heavy load, different wear resisting indexes were tested for different composites, among which, the SiC particles increased the index by the largest percent to 35%, while the index increases of composites added Gr + SiC were 7% separately compared with matrix alloy.

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