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Microstructural and abrasive wear properties of SiC reinforced aluminum-based composite produced by compocasting

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Abstract: The effect of SiC particles reinforcement with average size of 1, 5, 20 and 50 μm and volume fraction of 5%, 10% and 15% on the microstructure and tribological properties of Al-based composite was investigated. Composites were produced by applying compocasting process. Tribological properties of the unreinforced alloy and composites were studied using pin-on-disc wear tester, under dry sliding conditions at different specific loads. The influence of secondary mechanical processing with different rolling reductions on the dry sliding wear characteristics of Al matrix composites was also assessed. Hardness measurement and scanning electron microscopy were used for microstructural characterization and investigation of worn surfaces and wear debris. The proper selection of process parameter such as pouring temperature, stirring speed, stirring time, pre-heated temperature of reinforcement can all influence the quality of the fabricated composites. The porosity level of composite should be minimized and the chemical reaction between the reinforcement and matrix should be avoided.

Key words: aluminum matrix composite; hardness; wear; Al 6061; SiC particles

1 Introduction

Aluminium and its alloys have been broadly applied to various fields including car production, airplane industry and civil engineering due to the fact that aluminium has smaller density than steel, good resistance to corrosion and good mechanical and recycling properties [1−5]. This application is especially prominent within car and airplane industries because the application of aluminium parts provides smaller fuel consumption and at the same time it reduces production costs. Aluminium and its alloys are used for production of engine heads, engine blocks, cases for gearbox and differentials, carrying frame, car body panel, etc. The following aluminium alloys are most widely applied for the previously mentioned purposes: Al−Mg−Si alloys which are heat hardenable, weldable Al−Zn−Mg alloys, cold formed sheet metals based on Al−Mg and Al−Mg−Mn.

Aluminium matrix composites (AMCs) reinforced with ceramic particles are gaining wide spread popularity in several technological fields owing to their improved mechanical properties when compared with conventional aluminum alloys. They exhibit better mechanical properties than the unreinforced aluminium alloys and have been used as tribological parts in some vehicles for years due to their high specific strength and better wear resistance [6−16]. Presently, Al alloy based metal matrix composites are being used as candidate materials in several applications such as pistons, pushrods, cylinder liners and brake dics. Particulate-reinforced aluminum matrix composites have gained extensive applications in automotive and aerospace industries due to their specific characteristics. These include low density, high specific strength and stiffness, good fatigue properties, dimensional stability at high temperatures, and acceptable tribological properties [17−19].

There are several manufacturing techniques for particle reinforced MMCs such as liquid metal infiltration, spray decomposition, squeeze casting, compocasting, powder metallurgy and mechanical alloying. The conventional forging process has advantages in improving mechanical properties by removing defects of the alloys produced by casting process, whereas it has not enabled the lessening of the environmental impact because their gains are offset by the increased number of processes and reduced

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mold life. Currently, apart from conventional casting processes such as sand casting, permanent casting, and die casting, some other new casting techniques have been developed for Al alloys.

Semi-solid processing is typical example of this kind of new technique. In conventional casting, the primary dendrites normally grow and interact with each other. As a result, when only small amount of the melt (20%) freezes, the viscosity of the melt increases rapidly and the fluidity drops drastically. However, in semi-solid processing, the dendrites are broken by vigorous agitation during the solidification, and reasonable fluidity of the melt can be maintained until the solid content reaches as much as 60%. In addition, each broken dendrite becomes a separate crystal, which refines the grains without the addition of grain refiner. In this process, shrinkage and cracking of the casting are reduced because the alloy is already partly solidified when casting. Another advantage of this process is that the composite castings can be easily produced by adding fibers or particles (compocast). The application of this technique is still in its early stage and some brake cylinders and pistons have been manufactured by this process [20,21].

In recent years, among all the Al alloys, Al−Mg−Si alloys have been gained much popularity as a matrix material to prepare MMCs owing to their excellent mechanical properties and good corrosion resistance. AA6061 aluminum is used in the heat-treated condition in which an optimal ratio of physical and mechanical properties is obtained. The alloy solidifies in a broad temperature interval and is suitable for the treatment in the semi-solid state as well as as-cast condition [5−8]. The development of AA6061 aluminum matrix composites is of great interest in industrial applications for lighter materials with high specific strength, stiffness and heat resistance. Different reinforcing materials like SiC, TiB_2, Al_2O_3, zircon sand, SiCrFe, CrFeC, and cerium oxide have been used to reinforce the aluminum-based matrices in an attempt to improve their mechanical and wear properties [22−31]. Accordingly, the aim of the present study is to provide preliminary information on the effect of primary and secondary processing on the microstructure and tribological properties of a SiC reinforced aluminum-based composite produced by the compocasting. A comprehensive investigations are directed to the rheological behaviour and assessment of optimal parameters for semi-solid processing of this AA6061 alloy. Applying these processing, it is possible to obtain castings with reduced porosity, nondendritic structure and good wear properties.

2 Experimental

Composites used in this study were AA6061−SiC particles composites. The tribological properties of these grades of composites were evaluated using hardness and wear values obtained from cold rolled samples. AA6061 alloy having the nominal chemical composition shown in Table 1 was used as the matrix alloy. The composite was synthesized through a semi-solid processing route using SiC particles with average sizes of 1, 5, 20 and 50 μm, respectively as reinforcing particles. Silicon carbide is a material of particular interest due to its low density, high melting point and hardness. These properties make silicon carbide an attractive candidate for reinforcement of aluminium alloys when mechanical properties and wear resistance are demanded. Tables 2 and 3 show the properties of the Al matrix and SiC reinforcement, respectively. The stir casting furnace was mounted on the floor and the temperature of the furnace was precisely measured and controlled in order to achieve sound quality composite. In order to generate a semi-solid structure, the alloy system plays a key role where the co-existence of liquid and solid within a temperature range is the prerequisite for the slurry preparation. The process involved melting the alloy in the graphite crucible. The crucible was heated to about 680 °C in a resistance furnace. After melting the aluminum, the mixture was stirred at 600 r/min using an impeller fabricated from graphite and driven by a variable AC motor. The stirring time was noted at 10 min after the addition of SiC during the process.

Table 1 Chemical composition of AA6061 alloy (mass fraction, %)

Si	Fe	Cu	Mn	Zn	Ti	Mg	Cr	Al
0.43	0.7	0.24	0.139	0.25	0.15	0.8	0.25	Bal.

Table 2 Properties of AA6061 alloy

Elastic modulus/GPa	Density/($g \cdot cm^{-3}$)	Hardness (VHN)	Poisson ratio
70−80	2.7	107	0.33

Table 3 Properties of SiC particle

Elastic modulus/GPa	Density/($g \cdot cm^{-3}$)	Hardness (VHN)	Size range/μm
410	3.2	2600	1−70

The temperature of the furnace was gradually lowered until the melt reached a temperature in the liquid-solid state (corresponding to 20% solid fraction) while stirring was continued. The casting was obtained by pouring composite slurry into steel die placed below the furnace. A continuous purge of nitrogen gas was used inside and outside of the crucible to minimize the oxidation of molten aluminum. After casting, the specimens were annealed at 530 °C for 2 h, machined to samples of 150 mm length, 50 mm width and 10 mm thickness and cold rolled to different final reduction.

The cold rolled composites were characterized by wear testing. Dry sliding wear tests were carried out using pin-on-disc type wear tester at sliding velocity of 0.3 m/s within a load range of 10 to 40 N. Figure 1 shows the schematic diagram of the abrasion wear test. The disk was made of the steel hardened up to HRC 63 with a diameter of 50 mm and a thickness of 10 mm. The pin dimensions were 6 mm in diameter and 25 mm in length. The wear rates were calculated from the slope of mass loss versus sliding distance curves determined at several applied load levels within the range of 10 to 40 N. The wear rates measured in mass units were then converted to volumetric wear rates.

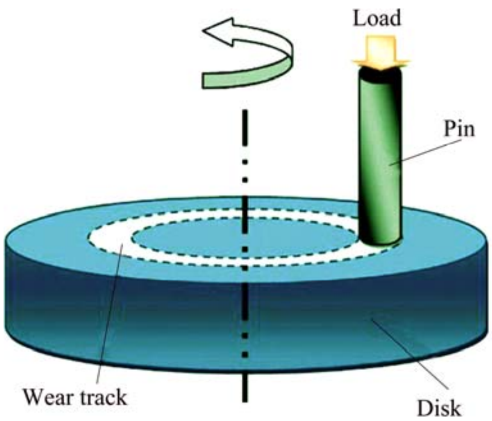


Fig. 1 Schematic diagram of abrasion wear test

The experimental density of the composites was obtained by the Archimedes method of weighing composites first in air and then in water, while the theoretical density was calculated using the mixture rule according to the volume fraction of the SiC particles. Metallographic samples were prepared using standard metallographic techniques, etched with standard aluminum etching solutions and examined by a optical microscope to determine the distribution of the SiC particles. The volume fraction of SiC particles was measured by means of an image analysis system attached to the microscope.

3 Results and discussion

The sliding wear of the composite is a complex process involving not only mechanical but also thermal and chemical interactions between two surfaces in contact. The wear resistance of composite materials is of our present interest because of their potential tribological characteristics that are very well applicable in automobile such as IC engines components, brake disc [25,26]. Figure 2 shows the wear rate of Al−SiC composites with different volume fractions of SiC during wear test at an applied load of 10 N. The addition of reinforcement improves the critical transition values of applied load and wear resistance compared with the corresponding matrix alloy. However, the increase of volume fraction of SiC can also provoke clustering of the particles during the fabrication of the composite. The strength of particles/matrix interface is very important parameter since interfaces could be relatively weak due to interfacial reaction and poor wettability. If the reinforcement is well bonded to the matrix, the wear resistance of composite increases continuously with increasing the volume fraction of reinforcement. In contrast, if the reinforcement is not well bonded to the matrix, the wear resistance of the composite increases up to a critical amount of the reinforcement and thereafter starts to decrease [27,28]. It is noted in Fig. 2 that the wear rate of the unreinforced alloy is higher than that of the composites. The lowest value of mass loss in wear test is distinct for Al−15%SiC and the highest mass loss in wear test is for bare Al alloy. Although the rate of change for the composites is smaller than that of the matrix, the wear rates of the matrix and the composites decrease with the sliding distance increasing. It is clear that the unreinforced matrix alloys wear more rapidly than the reinforced composite materials [22−24].

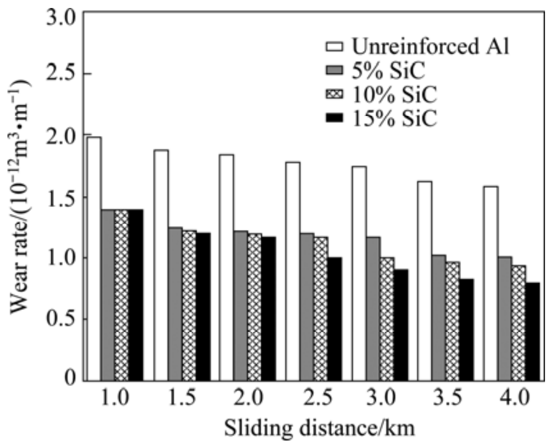


Fig. 2 Effect of sliding distance on wear rate of Al−SiC composites under an applied load of 10 N

It is known that the wear loss is inversely proportional to the hardness of alloys. In the case of unreinforced Al alloy, the depth of penetration is governed by the hardness of the specimen surface and the applied load. But, in the case of Al matrix composite, the depth of penetration by the harder asperities of hardened steel disk is primarily governed by the protruded hard ceramic reinforcement. Thus, the major portion of the applied load is carried by SiC particles. The role of the reinforcement particles is to support the contact stresses preventing high plastic deformation and abrasion between the contact surfaces and hence reduce the amount of worn material [19]. Figure 3 shows the hardness values for the unreinforced alloy and composites investigated in this study. It is observed that the addition of hard ceramic SiC particles increases the hardness of Al alloy.

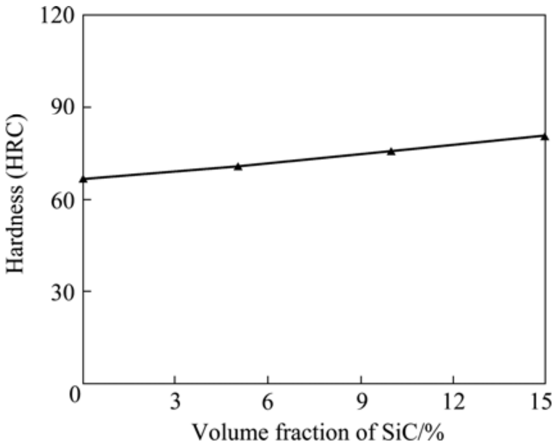


Fig. 3 Effect of SiC content on hardness of composites

The friction coefficient values of the matrix alloy and composite materials were in expected range for light metals in dry sliding conditions. Figure 4 shows that the friction coefficients for composites containing SiC are higher than those for the aluminum-based alloys while sliding under identical conditions. It is shown that in these sample pins deform plastically which result in low friction coefficient. The higher coefficients of friction in the case of composites containing hard SiC particles are due to the formation of tribofilm at the interface between pin and disk. If the effective load on the individual particle is above its flexural strength, the particles get fractured. Parts of the removed SiC particles are entrapped between two partners, i.e. asperities of softer material of pin and asperities of harder material (hardened steel disk), possibly leading to three-body abrasion; then it will result in more surface roughness between contacting surfaces and increase of coefficient of friction [25−29].

The increase of the coefficient of friction with the amount of reinforcement particles is ascribed to the fact that the amount of protruded particles increases during wear occupying larger area of pin surface. In the same time, one part of protruded particles are torn away from the matrix and fractured into fragmented pieces. In this situation, the contact between the hard particles and the counter body material is established, resulting in higher coefficient of friction. Compared with the matrix alloy,

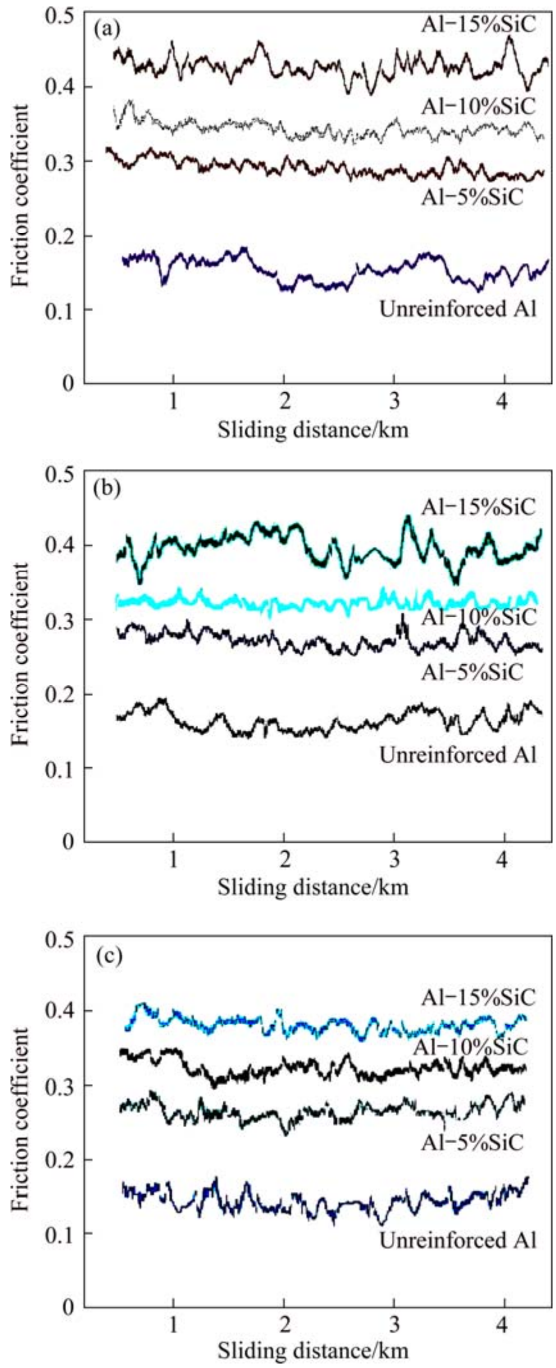
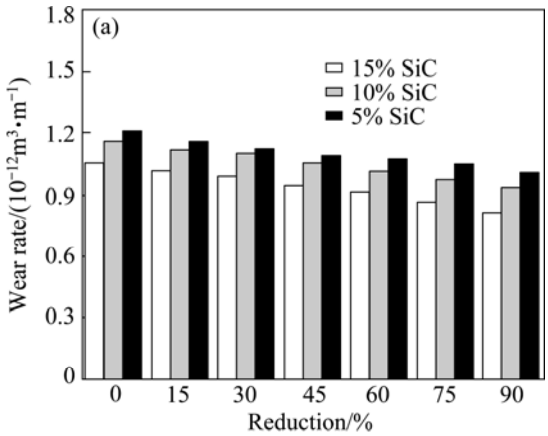
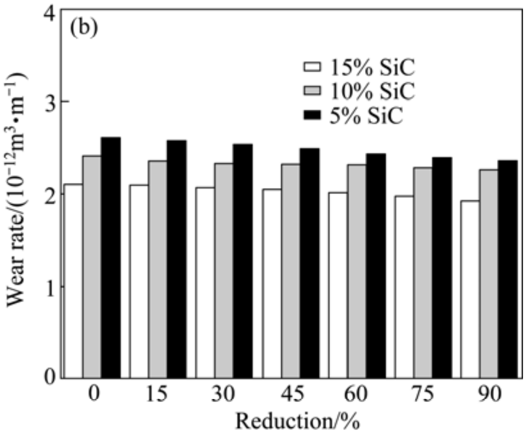


Fig. 4 Effect of sliding distance on coefficient of friction of composites under different applied loads: (a) 10 N; (b) 20 N; (c) 40 N

higher coefficient of friction of composite corresponds to lower value of the wear rate [26−31].

Figures 5 and 6 show the wear rate and hardness results of the as-cast and cold rolled composites. The application of cold rolling is assumed to enhance the mechanical properties of the matrix alloy. It is known that the incorporation of particulate reinforcements brings an increment in the material tensile strength and promotes the load transfer from the matrix to the reinforcement phase. Even though problems such as





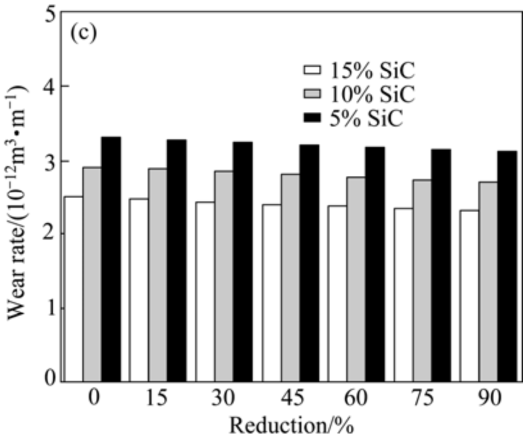


Fig. 5 Effect of rolling process on wear rate of composites under different applied loads: (a) 10 N; (b) 20 N; (c) 40 N

reinforcement clustering, cracks in the reinforcement surface, or poor bonding between the matrix and reinforcements prevent the enhancement of the composite strength, excellent bonding is obtained between the matrix alloy and reinforcement as a result of rolling, and increased content of reinforcement in the matrix alloy leads to increased dislocation densities during solidification due to the thermal mismatch between AA6061 alloy and SiC particles, resulting in retardation in plastic deformation. Higher dislocation densities together with the reinforcement particles will result in hindered dislocation movement and thus higher

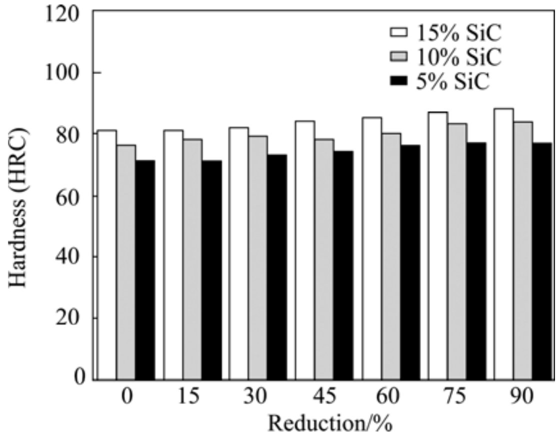


Fig. 6 Effect of rolling process on hardness of composites

hardness. It is observed that there is an improvement in wear resistance of the cold rolled composites which might be explained by the increase in the hardness of them.

The homogenous distribution of the reinforcement phase is an essential condition for a composite material to achieve its superior performance. Particularly in the case of discontinuous MMCs, the homogeneous distribution of the reinforcing phase is an essential requirement. Microstructural characterization of the samples shows that the fabrication of composites via compocasting technique plus cold rolling (reduction of 90%) leads to reasonably uniform distribution of particles in the matrix and minimum clustering or agglomeration of the reinforcing phase and thus higher hardness and wear resistance. Typical optical micrographs of the unreinforced Al alloy and the compocast SiC reinforced Al alloy composites are shown in Fig. 7. The presence of the reinforcement particles in the Al matrix and the difference between the microstructures of 0 and 90% cold rolled samples produce a great difference in their wear rate, as shown in Fig. 5, a confirmation of the effectiveness of the cold rolling process. The globular microstructure of the composites in this study is desirable as it results in good mechanical and tribological properties of the product. Such microstructure is achieved by enhancing the fluid flow in the mush during solidification by means of stirring. The stirring is one of the most effective means to obtain globular microstructure in the cast product. The strong induced fluid flow detaches the dendrites from the solid−liquid interface during solidification and carries them into the mold to form a slurry. In the slurry, the detached dendrites coarsen and rosette or globular particles form based on the process conditions. The resultant semi-solid slurry offers less resistance to flow even at a high solid fraction and can easily flow into the die-cavity.

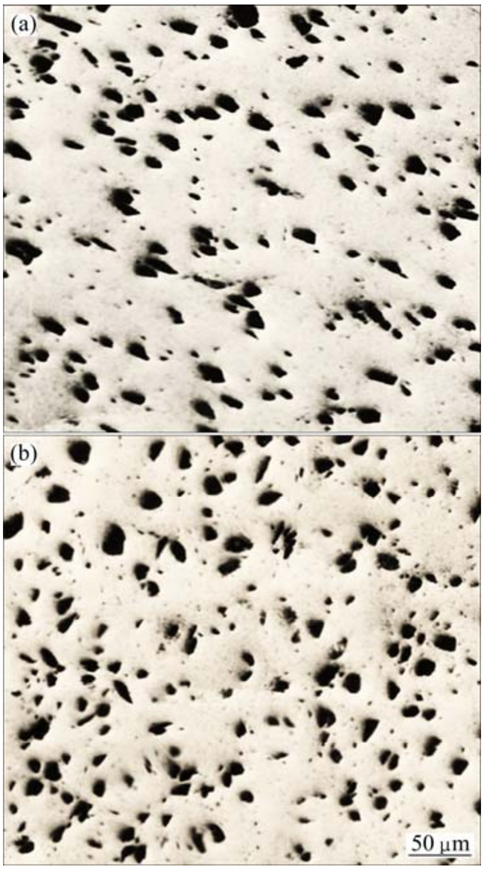


Fig. 7 Optical micrographs of as-cast Al−10%SiC (a) and 90% cold rolled Al−10%SiC (b)

The mechanics and mechanisms of the primary particles' evolution are a concern since the formation of globule morphology is expected to enhance die filling and improve mechanical properties of as-cast parts. The ideal microstructure for the slurry is individual fine spherical solid particles uniformly distributed within a liquid matrix. The solid fraction should be considered carefully, since a low-fraction solid may lead to handling and mold-filling problems due to insufficient viscosity and turbulence. High fraction of solids, however, may have die-filling troubles or increase the cost of machinery.

It is also noted in Fig. 5 that the wear rate for all the samples increases marginally with the applied load increasing. The increase in the applied load leads to increase in the penetration of hard asperities of the counter surface to the softer pin surface, increase in micro cracking tendency of the subsurface and also increase in the deformation and fracture of asperities of the softer surface.

The wear surface of the unreinforced alloy under the applied load of 20 N is depicted in Fig. 8. The unreinforced matrix alloy is much softer than the counter body material, and during sliding the counter body penetrates into the matrix alloy, producing deep grooves and causing extensive plastic deformation of the surface, which results in great material loss and significant wear rate. The worn surfaces also contain the evidence of adhesive wear in the form of adhesive pits. On the other side, the large scale of the matrix alloy is transferred to the counter body. The flow of materials along the sliding direction, the generation of cavities due to the delamination of surface materials and tearing of surface material are also noted in this figure. The worn surface of the as-cast and cold rolled 5% SiC composite under an applied load of 20 N is shown in Fig. 8. It indicates the formation of continuous wear grooves, relatively smooth MML and some damaged regions. However, the degree of crack formation on the wear surface is not much. The wear surface is characterized by the formation of parallel lips along the continuous groove marking.

Morphology of worn surface and size of wear debris collected during the tests are also shown in Fig. 8. Debris generated by the wear of materials originates mostly from the pin material. Some plate-like particles can be found among the wear debris of Al matrix alloy and the composites with low volume fraction of SiC. On the surface of these plate-like particles, the presence of material plastic flow could be noticed. Thus, at higher specific load, the wear debris are mainly plate-like with sharp edges, which are typical of adhesive wear. The presence of the rod-like particles also indicates the existence of severe wear. Analyses of pin and counter body worn surfaces and generated wear debris show that the predominant mechanism of wear is adhesion followed by plastic deformation. Sporadic deep caverns formed by the pull-out of SiC particles from the matrix indicate relatively weak interfacial bonding between the aluminium matrix and SiC particles in these areas. These SiC particles, fractured into fragmented pieces, entrapped between the pin and the counter body, and together with the protruded SiC particles from the matrix act as abrasives. The presence of brown layer on the pin worn surface as well as brown-coloured wear debris indicates the formation of the iron oxides and the existence of the oxidation wear. SEM images of composite indicate that the wear debris is finer than those from the matrix alloy. Analyses of pin and counter body worn surfaces and generated wear debris show the presence of the steady-state mild wear.

Defects such as clusters of reinforcement particles impair the mechanical and tribological properties of the composite. Differences in particle sizes, densities, geometries, flow or development of an electrical charge all contribute to particle agglomeration. The uniformity in distribution of particles within the sample is a microstructural feature which determines the in-service properties of particulate AMCs. A non-homogeneous particle distribution in cast composites arises as a result

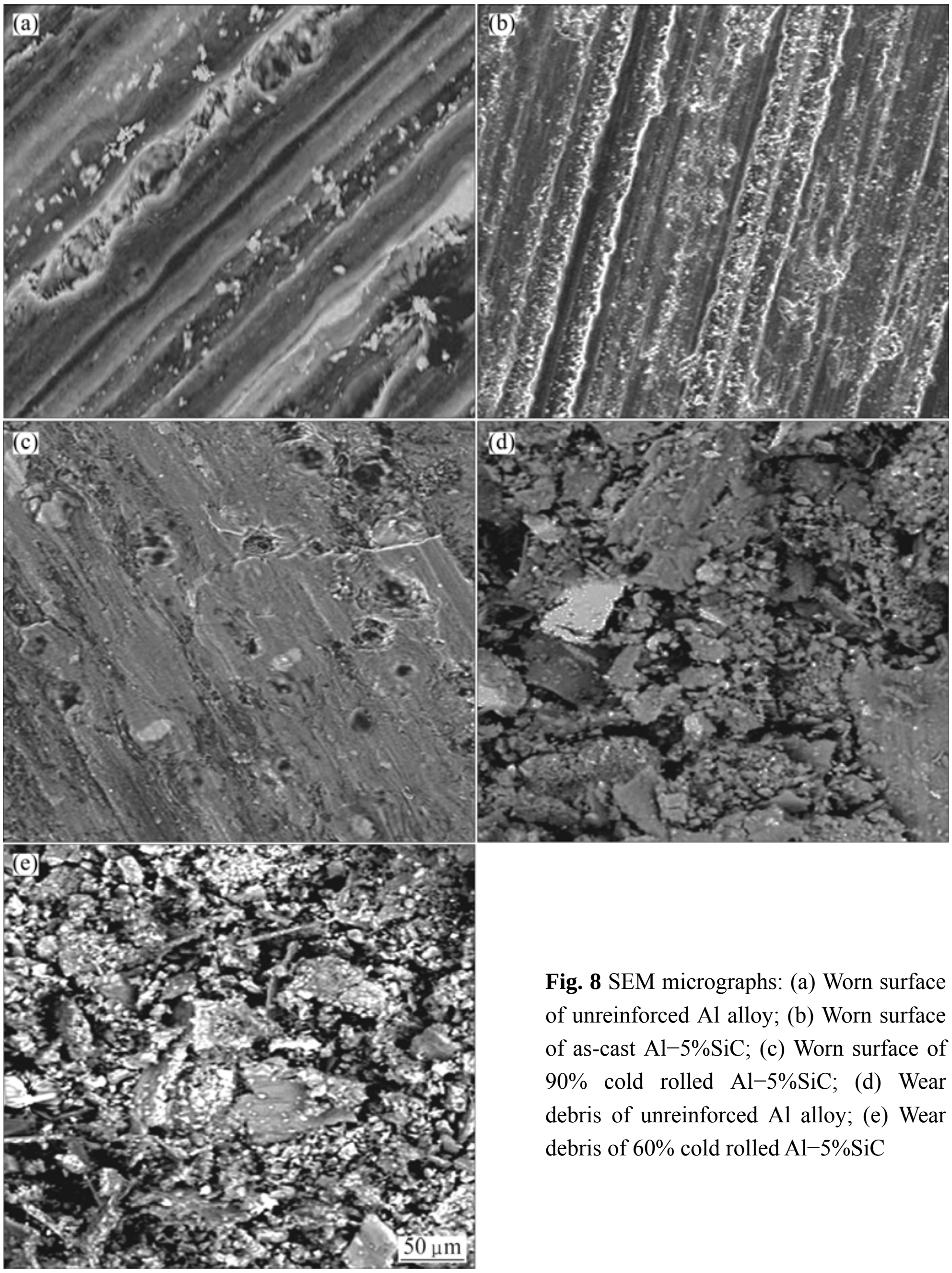


Fig. 8 SEM micrographs: (a) Worn surface of unreinforced Al alloy; (b) Worn surface of as-cast Al−5%SiC; (c) Worn surface of 90% cold rolled Al−5%SiC; (d) Wear debris of unreinforced Al alloy; (e) Wear debris of 60% cold rolled Al−5%SiC

of sedimentation (or flotation), agglomeration and segregation. The subject of particle distribution in particulate MMCs has been studied by several investigators either qualitatively or quantitatively. The macroscopic particle segregation due to gravity (settling) has also been studied both experimentally and theoretically, the latter of which generally involves the correlation of particle settling rate within the composite slurry with the Stocks' low [29−31]. A sedimentation experiment was conducted on the composites containing 10% (volume fraction) particles. Figure 9 shows the SiC concentration as a function of the distance from the bottom of the mould. It is noted that the particle distribution in the cold rolled composites is much more uniform than that in the as-cast one. As can be seen, the lower parts of the as-cast ingot contain a higher volume fraction of particles than the upper parts, representing an uneven macroscopic particle distribution.

During the solidification process of the composite slurries, the reinforcing particles are pushed to the interdendritic or intercellular regions and tend to segregate along the grain boundaries of the matrix alloy. The quantitative assessment of the SiC particle distribution within composite samples was performed by considering the distribution factor (F) defined as

$$F=\sigma/A_{\mathrm{f}}$$

where A_{f} is the mean value of the area fraction of the SiC and σ is its standard deviation. Figure 10 shows the gradual decrease in distribution factor for the composites when the particle content and cold rolling reduction increase, indicating the improvement in the uniformity of the SiC particle distribution. These results can be attributed to the occurrence of deagglomeration process in the cold rolled composites. Deagglomeration phenomenon is the result of high deformation ratio applied to the aluminum matrix. Plastic flow of the aluminum matrix causes the SiC clusters to break and get separated from each other, resulting in a more uniform distribution of the particles in the matrix. Enhanced amount of SiC particles prevents severe wear by protecting the soft matrix and improving wear resistance. Thus, if the particles remain well bonded with the matrix during sliding, the aluminium matrix that surrounds the particulates will be worn away, and essentially all contact will be between the reinforcing particles and the counter body. All forces developed during sliding will be preserved in contact between SiC particles and the counter body, and for this reason, the shear stress at the SiC particle/matrix interface may cause particle decohesion. The wear rate will be then largely controlled by the wear rate at which particles decohere.

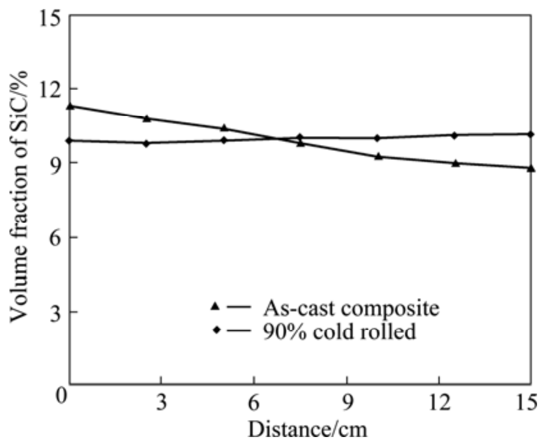


Fig. 9 SiC content as function of distance from bottom of mould

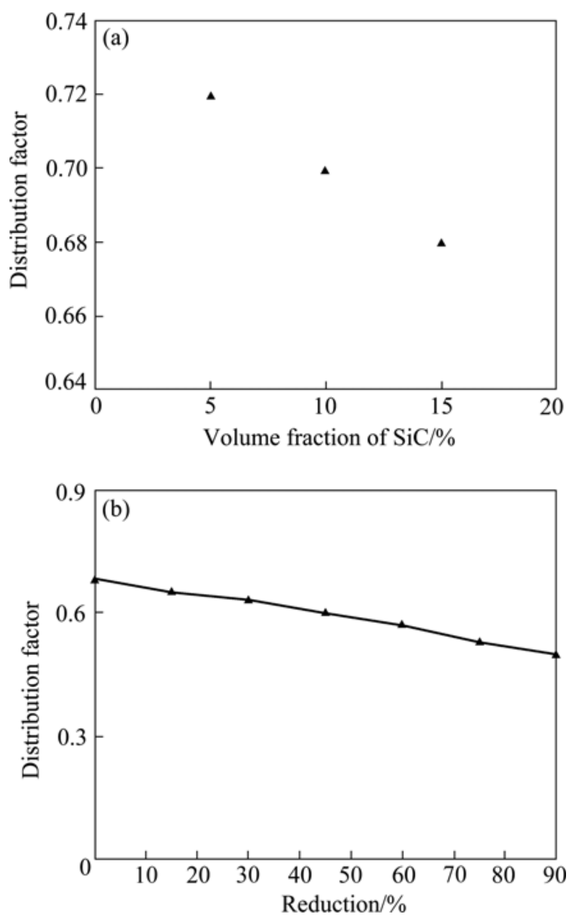


Fig. 10 Distribution factor vs volume fraction of SiC (a) and reduction (b)

Figure 11 shows the effect of the rolling process on the porosity of the composites. The cold rolling process is able to produce practically full-density materials. It is confirmed that the application of cold rolling produces a composite material with better distribution of the reinforcement particles, and to some extent small decrease in the size of reinforcement particles is observed. The high energy involved should be sufficient to break the clusters of reinforcement particles, to eliminate most of the weak points, such as surface cracks, present in the reinforcement particles, and to promote a significant decrease in the reinforcement particle size. These effects are so significant in the present case, in part due to the characteristics of the particulate reinforcement, such as its morphology and hardness. The use of brittle reinforcement particles produces great fragmentation, resulting in a fine distribution of the reinforcement phase.

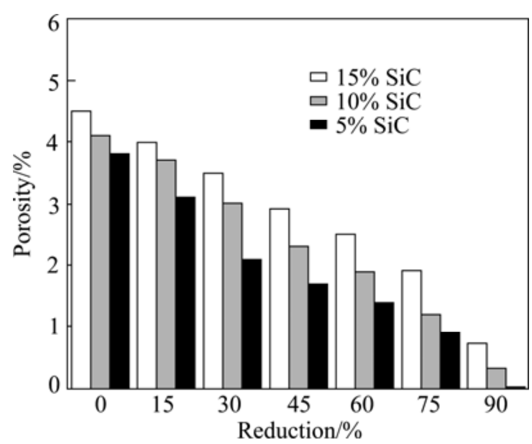


Fig. 11 Effect of rolling process and SiC volume fraction on porosity of composites

It is noted that the application of the heavy reduction (90%) during cold rolling process results in almost no porosity. Porosity formation in cast metal matrix composites can be attributed to the air trapped in the clusters of particles as well as the hindered metal flow inside them. It also indicates that increasing the amount of porosity is observed with increasing the volume fraction of SiC particulates. The porosity level increases, since the contact surface area is increased. This is attributed to pore nucleation at the SiC particulate sites (porosity associated with individual particle) and to hindered liquid metal flow due to more particle clustering (porosity associated with the particle clusters).

4 Conclusions

1) The decreased porosity of composites during rolling is due to the flow of matrix alloy under the applied shear and compressive forces which result in filling of the voids. The increased rolling reduction provides easier flow of the matrix alloy and hence results in decreased porosity. In fact, the major reason for rolling the particulate metal matrix composites (PMMCs) is to close the pores and attain improved mechanical properties.

2) The microstructural studies revealed the more uniform distribution of the particles in the matrix of the cold rolled samples. Microstructure of the composites revealed that during the compocasting process a transformation from a typical dendritic to a nondendritic structure of the primary α phase occurred as a result of shear forces generated by the mixer rotation.

3) It can be seen that the hardness of tested materials increases with the increase of SiC particles amount. The matrix hardness exerts a strong influence on the dry sliding wear behaviour of the SiC particles reinforced composite, and the composite with the lowest matrix hardness displays the lowest wear rate.

4) The applied load has a significant influence on the wear rate of tested materials. In general, with the increase of the applied specific load the wear rate of the matrix and composites also increases.

5) Unreinforced Al alloys show very intensive wear rate from the beginning of the test. Wear behaviour is determined by extensive material plastic flow on pin surface indicating severe wear regime as dominant. However, composite does not show plastic deformation on the worn surface.

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搅拌铸造 SiC 颗粒增强铝基复合材料的组织与磨损性能

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摘　要：研究 SiC 颗粒增强体(粒径为 1、5、20 和 50 μm；体积分数为 5%、10%和 15%)对 Al 基复合材料组织和磨损性能的影响。采用搅拌铸造工艺制备复合材料，采用盘−销式磨损试验测试 Al 基体和复合材料在不同载荷下的干滑动摩擦磨损性能。考察冷轧压下量对复合材料干滑动磨损性能的影响。对磨损表面和磨屑进行硬度测试和 SEM 观察。结果表明，搅拌铸造工艺参数包括浇注温度、搅拌速度、搅拌时间、增强体颗粒预热温度等影响所制备材料的质量。为使材料具有较好的性能，应将复合材料中的孔隙度降至最小，尽量避免增强体颗粒与基体之间的化学反应。

关键词：铝基复合材料；硬度；磨损；6061 铝合金；SiC 颗粒

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