Influence of mechanical alloying on the mechanical and tribological properties of SiC particle reinforced aluminum matrix composites

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Al-Cu-Mg alloy and its matrix composites reinforced by silicon carbide(SiC) particles have been prepared by powder metallurgy(P/M) method. The effects of mechanical alloying technique and SiC particles on the mechanical properties, wear rate and friction coefficient were studied. The results show that the composites have better mechanical and tribological properties than the matrix alloy. When the volume fraction of SiC particles is 9%, the SiCp/Al-4wt%Cu-4wt%Mg composite has the best performances, such as, highest strength, lowest wear rate and lowest coefficient. Mechanical alloying further improves the hardness and tensile strength and shifts its optimal magnesium content of the alloy from 1.2wt% to 0.8wt%. However, mechanical alloying hardly influences the wear rate, and slightly affects the friction coefficient of the composite.

1. Introduction

Particles reinforced aluminum matrix composites are gaining extensive application in several technological fields such as aerospace, automobiles and civil architecture industries due to their specific characteristics [1~8]. These include lower density, higher strength, dimension stability at high temperatures, and other better mechanical properties than the unreinforced aluminum alloy. Especially, because of their high specific strength and better wear resistance, they have been used as tribological parts in some vehicles such as pistons, pushrods, cylinder liners and brake discs.

There are several manufacturing techniques [8~20] for particle reinforced metal matrix composites such as liquid metal infiltration, spray decomposition, casting, powder metallurgy and mechanical alloy. The major problem for metal matrix composite process is obtaining a homogeneous distribution of the particles [1, 17, 18]. Another main problem is that aluminum carbide (Al_4C_3) phase is prone to form on the interface [1, 19] because of SiC thermodynamically unstable to Al during fabrication of aluminum matrix composite reinforced by SiC particles. Powder metallurgy (P/M) somewhat solves the problems through mixing uniformly the solid componential powders before pressing, lowering the temperature and holding time to reduce the interface reaction.

Mechanical alloying (MA) is defined as a high-energy milling process for producing composites with a fine microstructure. At initial stage, it is used to prepare nickel-based superalloy [21~23]. In aluminum matrix composites, mechanical alloying technology [24~26] can make the components uniformly distribute, further facilitating the uniform distribution of particles. Also, it refines the ceramic particles to sub-micron or nanometer size. Nowadays, sub-micron or nanometer particulars reinforced metal matrix composites are little researched [27, 28] because the sub-micron or nanometer particulars are prone to aggregate and difficult to be dispersed evenly in the matrix. In this paper, sub-micron SiC particle reinforced Al-Cu-Mg matrix composites was prepared in powder metallurgy (P/M), and the effects of mechanical alloying technique and the influence of SiC particle volume friction on the mechanical properties, wear rate and friction coefficient of the composites were investigated.

2. Experiment

2.1 Material preparation

The raw materials are listed in Table 1. The SiC particles were milled for 4 hours in a high energy ball mill

and hold at 800 °C for 3 h to get rid of impurity, organic materials and vapor to improve the compatibility between silicon carbide and aluminum matrix. Fig. 1 shows that the pre-treated SiC particles are approximately global with sub-micron sizes of 100~300 nm.

Table 1. Raw materials.

Raw Material	Fineness	Purity
Copper powder	200 mesh	99.5%
Aluminum powder	200 mesh	99.5%
Magnesium powder	200 mesh	99.5%
SiC particles	200 mesh	98%
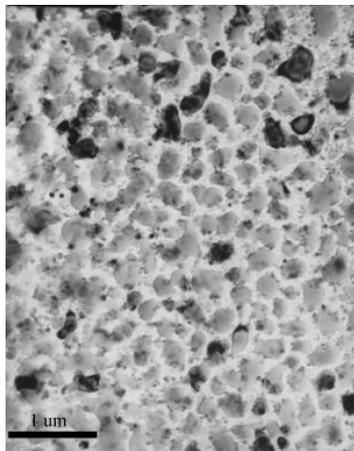
Fig. 1. TEM photograph of pre-treated SiC particles.

First, Al-4wt%Cu-0.4wt%Mg matrix composites reinforced by sub-micron SiC particles with different volume fractions (Vf) are prepared by P/M method. The proper amount of aluminum, copper and magnesium powders and pre-treated SiC particles were mixed by hand in a mortar with ethanol, cold compacted under a 300 MPa pressure to a block size of $0.060m \times 0.010m \times 0.004m$ at room temperature, and sintered at 400 °C for 30 min followed by 570 °C for 2 h under argon protection. The sintered specimens were held at 500 °C for 40 min, quenched in cold water and naturally aged at room temperature for more than 96 hours.

Then the 9Vf%SiCp/Al-4wt%Cu-Mg composite with different magnesium contents of the matrix were prepared. These samples were divided into two groups according the powder mixing processes: by hand or by MA. In MA process, stainless steel balls are used, the mass ratio of balls to powder is 10:1, the rotation speed is 185 rpm and the milling time is 4 h in a high-energy ball mill with a protective argon environment. In order to eliminate to work hardening and improve compressibility, the alloyed powder mixtures were annealed at 350 °C for 30 min in vacuum circumstance. X-ray diffraction (XRD) analyses were done after milling for a certain period to exam the composition changes during the process.

2.2 Property measurements

The samples were polished before measurements. Their density was determined by Archimedes principle, and the ratio of measured density to the theoretical density was defined as the calculated compactness of the specimens. A Vickers hardness (HV) was measured and each value was the average of six readings for each sample. Tensile strength was tested on an electronic universal testing machine, where a displacement control regime was used at a constant displacement rate of 0.001 m per minute, and the specimens were stretched until failure and the failure load was recorded automatically. The ultimate tensile strength (UTS) of the specimen is calculated by the formula

$$UTS = \frac{F_{max}}{W * t} \qquad (1)$$

Where F_{max} is the maximum load, W is the fracture width of the specimen, and t is the specimen thickness.

Friction and wear properties of the specimens were tested using repeated sliding form under a dry wear condition at room temperature. The friction coefficients were measured for 5 min at 0.5 N and 2 N loads respectively. The frequency was 10 Hz and the track length was 5 mm. The tester recorded the coefficients automatically.

The wear rate was measured using a pin-on-block mode on the wear tester. The specimen was used as a block and the 4 mm diameter pin was made of high speed steel with hardness of Rockwell C-scale (HRC) 62, which was renewed for each sample. During sliding wear tests, test samples were placed on the wear machine and the sling wear tests were carried out in an increment mode, i.e. 400 m per increment and a total distance of 2 000 m. Wear tests were carried out with constant sliding velocity of 0.17 m s $^{-1}$ at 2 N and 3 N loads. After each increment, the specimen was removed, cleaned, weighted with a balance to an accuracy of 0.1 mg and then remounted in the wear tester at the same location. The wear rate (W_s) is used to estimate the abrasion resistance and calculated according to the following formula

$$W_s = \frac{\Delta V}{pL} \qquad (2)$$

Where, p is the test load, L is sliding distance, and ΔV is the volume loss, which is calculated according to its density and the mass loss.

2.3 Analyses

The appearances of pre-treated SiC particles were observed by TEM technique on a transmission electron microscope. The powder mixture compositions during mechanical alloying were analyzed by XRD analysis technique. Powder mixture, fracture surfaces, the worn surfaces and the pin counter-face were observed by a scanning electron microscope (SEM). The transferred mass components on the pin counter-faces was analyzed by a energy dispersive spectrum (EDS).

3. Results and discussions

3.1 The mechanical properties of SiCp/Al-4wt%Cu-0.4wt%Mg composites

Figs. 2 and 3 reveal the influence of heat treatment and SiC volume fraction on the density and mechanical properties of the SiCp/Al-4wt%Cu-0.4wt%Mg composites respectively. They show that the heat treatment improves the density, compactness, hardness and tensile strength of the composites. With the SiC particle volume fraction increasing, the density and compactness of the composites gradually changes. The hardness and tensile strength increase first and then reach the ultimate value at 9 Vf%.
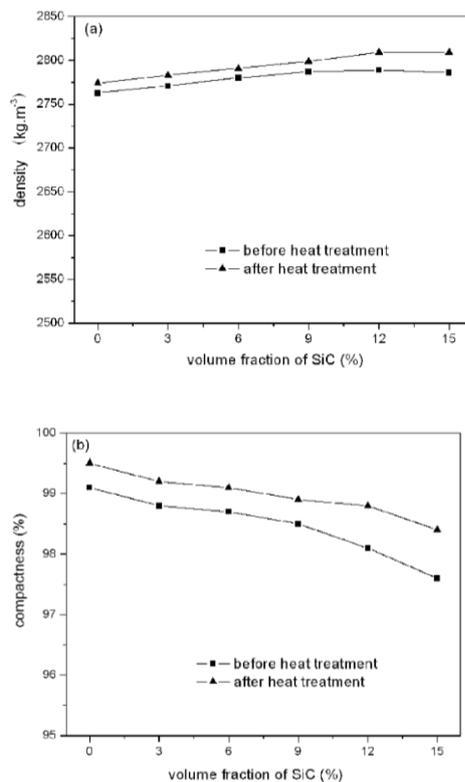
Fig. 2. The relationships of heat treatment, SiC particles and density of the SiCp/Al-4%Cu-0.4%Mg composites, (a) density, (b) compactness.
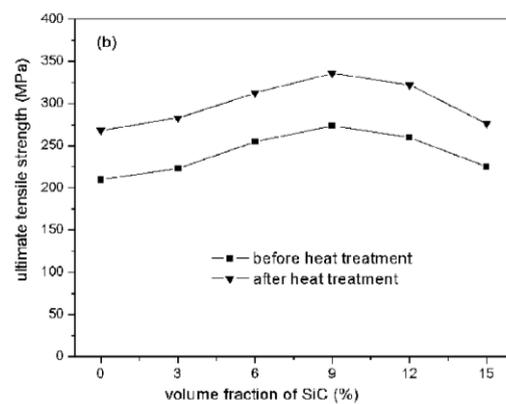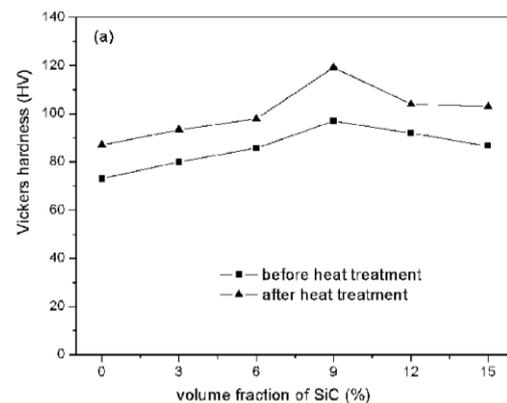
Fig. 3. The relationships of heat treatment, SiC particles and mechanical properties of the SiCp/Al-4%Cu-0.4%Mg composites, (a) hardness, (b) ultimate tensile strength.

These property characteristics are mainly attributed to the dispersion strengthening of the fine SiC particles and precipitation strengthening after aging. As the fraction of SiC particles increases, the matrix transfers the load to the reinforcement particles more efficiently. However, the bonding force between the SiC particles and matrix is somewhat weak, and the interface between them even provides the crack sources, which affect the load transferring and accelerates fracture in the tensile test. When the effects of these opposite factors are balanced, the materials have the optimal mechanical properties. In this experiment, the composite with 9 Vf% SiC particles (9Vf%SiCp/Al-4%Cu-0.4%Mg) has the optimum mechanical performance.

3.2 Effects of mechanical alloying on the mechanical properties of the composites

Selecting 9Vf%SiCp/Al-4%Cu-0.4%Mg composite as the basic material, we adjusted the magnesium content in the matrix to further improve the mechanical properties. Fig. 4 shows the effects of MA process on the hardness and ultimate tensile strength of the composite after heat treatment. It is seen that MA process raises the hardness

and ultimate tensile strength of the composites, and shifts the optimal magnesium content in the matrix from 1.2 wt% (mixed by hand) to 0.8 wt% (mixed by MA) with the optimum mechanical performances. These perhaps are concerned with the characteristics of powder mixture.
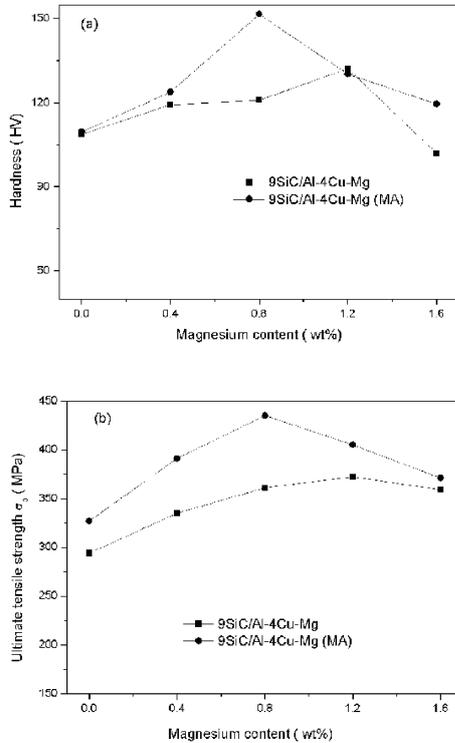
Fig. 4. Effects of MA on the magnesium content of 9Vf%SiCp/Al-4%Cu-Mg composites, (a) hardness, (b) ultimate tensile strength.

Fig. 5 shows the morphology of powder mixture of by hand and by MA. Fig. 5a shows that a mechanical mixture is formed by hand, and the SiC particles distribute unevenly and aggregate obviously. While in fig.5b, the all component powders are broken into pieces, the SiC particles distributed uniformly with the metal powders, and an alloyed mixture are formed. Much finer powders with more structure defects make atoms' inter-diffusing more easily that improves the sintering properties and the mechanical properties after heat treatment.

X-ray diffraction (XRD) shows that the component element peak values and locations change at all stages during MA process (see Fig. 6). All element peaks exist evidently after milling for 1 h and get weak after milling for 2 h. The magnesium peak disappears after milling for 4 h, meanwhile aluminum and copper peaks increase again. Magnesium peak disappearing means that magnesium completely dissolves into the matrix and the alloyed powders of a solid solution form after milled for 4 h in the high energy ball mill.
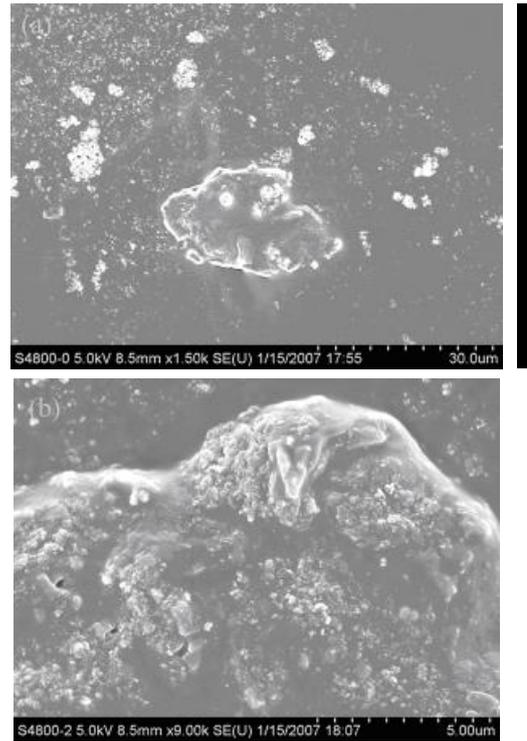
Fig. 5. SEM images of the different powder mixture (a) by hand; (b) by MA.
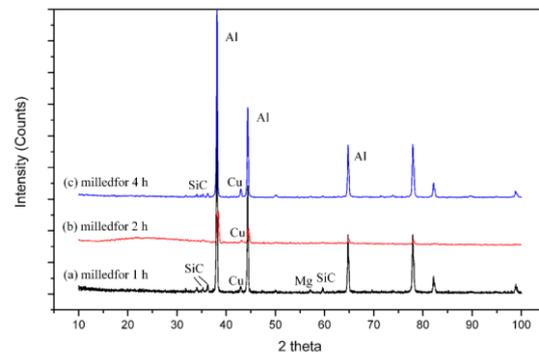
Fig. 6. XRD analysis of powder mixture during mechanical alloying.

3.3 The tribological properties of SiCp/Al-4wt%Cu-0.8wt%Mg composite

Selecting Al-4wt%Cu-0.8wt%Mg as the matrix composition of the composites, we investigated the wear rates and friction coefficients of the composites and the matrix alloy. These results are shown in Figs. 7 to 9.

In Fig. 7, the wear rate of the matrix alloy changes acutely, while those of the composites are quite stable, nearly constant and much lower than that of the matrix alloy at the same load. And the wear rate of the composites at 2 N load is much lower than that at 3 N load, especially for matrix alloy.
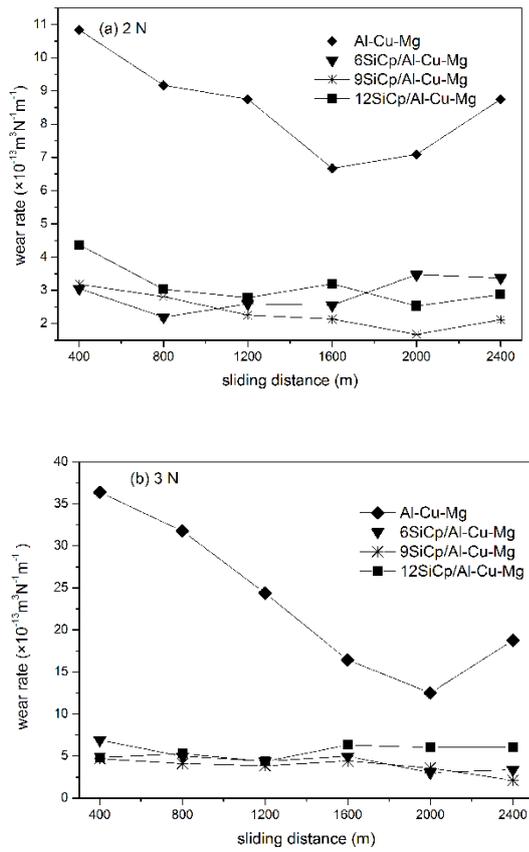
Fig. 7. The wear rate of the SiCp/Al-4%Cu-0.8%Mg
composites, (a) at 2 N, (b) at 3 N.

Fig. 8 shows the relationships of the loads, SiC volume fraction and the wear rate of SiCp/Al-4%Cu-0.8%Mg composites after sliding for 400 meters. It can be seen that, with the SiC volume fraction increases, load less affect the wear rate. The wear rate of the matrix alloy was influenced distinctly by the load, but that of the composites rarely affects.
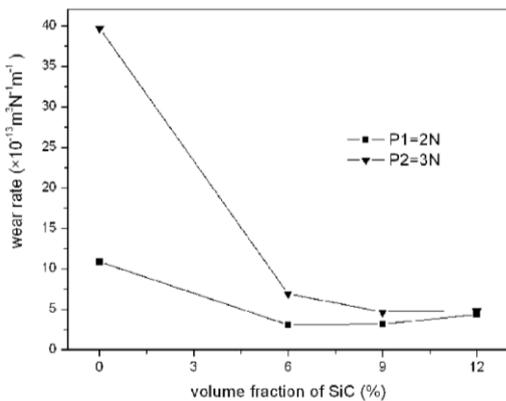
Fig. 8. Effect of loads on the wear rate of
SiCp/Al-4%Cu-0.8%Mg composites (sliding distance
of 400 meters).

Fig. 9 shows the friction coefficient of the matrix alloy and the SiCp/Al-4%Cu-0.8%Mg composite. It is seen that the coefficient drops with the SiC volume fraction increasing, where 9Vf%SiCp/Al-Cu-Mg composite has the lowest friction coefficient, while the matrix alloy and 6Vf%SiCp/Al-4%Cu-0.8%Mg composite have nearly the same friction coefficient, which is higher than those of the other composites.
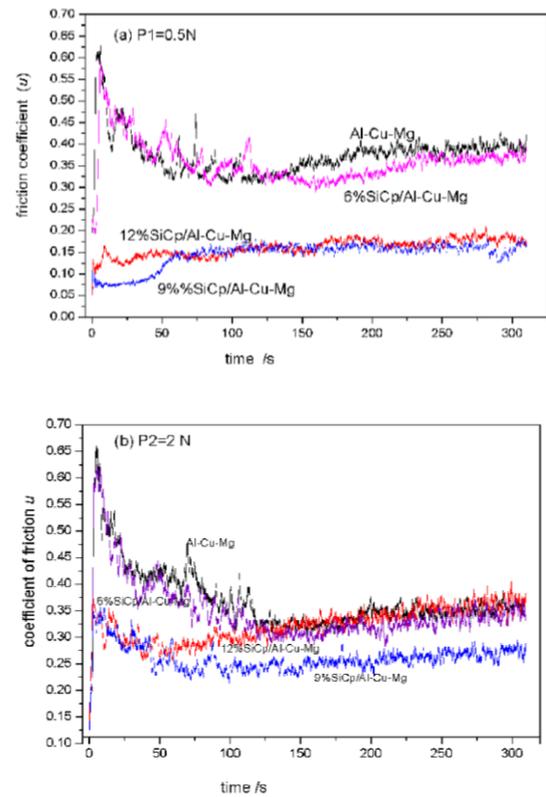
Fig. 9. The friction coefficient of the SiCp/Al-4%Cu-0.8%Mg
composites, (a) at 0.5 N, (b) at 2 N.

The tribological performances are concerned to material hardness, work hardening and high temperature strength after temperature risen on the surfaces. In the composites, the tough SiC particles are uniformly distributed in the soft aluminum matrix, hindering the movement of grain boundaries and improving the mechanical properties, see Figs. 2 and 3. Furthermore, in sliding concaves appear on the matrix and SiC particles protrude to bear a majority of load, decreasing the contact area between composite and the sliding pin, accelerating the heat convection, and reducing the adhesive trend.

3.4 Effects of MA process on the tribological properties of the materials

The effects of MA on the tribological properties of 9Vf%SiCp/Al-4wt%Cu-0.8wt%Mg composite and its matrix alloy are revealed in Figs. 10 and 11.

In Fig. 10, the wear rate of the composite is distinctively lower than that of the alloy at the same load whether mixed by MA or by hand. MA process does not affect the wear rate of the composite, but slightly changes that of the matrix alloy, especially at the heavier load of 3 N.
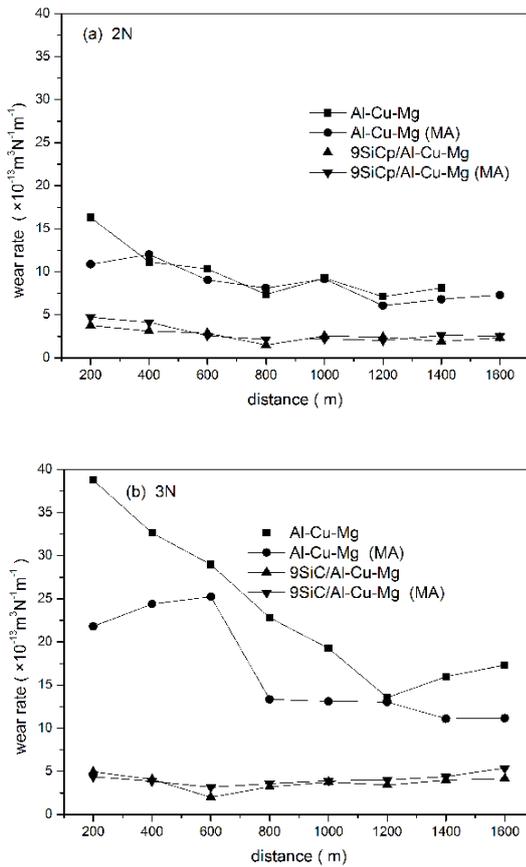
Fig. 10. Effect of MA on the wear rate of 9Vf.%SiCp/Al-4%Cu-0.8%Mg composite and its matrix alloy, (a) at 2 N, (b) at 3 N.

Fig. 11 shows the effect of MA on the friction coefficient of 9Vf%SiCp/Al-4%Cu-0.8%Mg composite and its matrix alloy. It can be seen that MA raises the friction coefficient of the composite at the two loads, while it does not affects that of the matrix alloy.
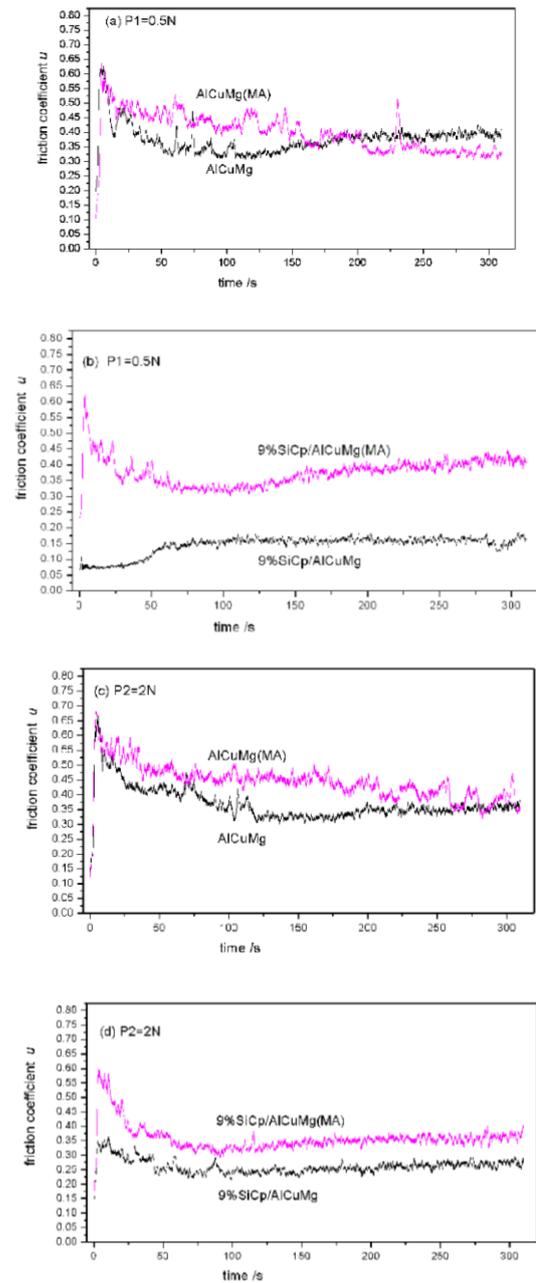
Fig. 11. Effect of MA on friction coefficient of 9Vf%SiCp/Al-4%Cu-0.8%Mg composite and its matrix alloy, (a) matrix alloy at 0.5 N, (b) 9%SiCp/Al-Cu-Mg composite at 0.5 N, (c) matrix alloy at 2 N, (d) 9%SiCp/Al-Cu-Mg composite at 2 N.

Figs. 12 and 13 respectively show the SEM morphologies of the worn surfaces of the blocks and couple pin surfaces after dry sliding for 1600 meters under 3N.

process has the narrowest ones, see Fig. 12c. There are many furrows, desquamations, white dots and continuously white webbings on the worn surfaces of the matrix alloy and MA composites, which imply that their adhesive and oxidation wear mechanisms.

SEM images of the pin surfaces show that there is a lot of mass adhesion, see Fig. 13, which indicates mass transferring from the worn specimens. In addition, Fig. 13a shows a lot of white dotes and fraction lets, which prove an abrasive mechanism. Thus, the composites produced by hand mixing have a combination of abrasive and adhesive wear mechanisms. There are fewer white dots and adhesive mass on the pin surfaces coupled with composite prepared by MA, see Fig. 13b, which implies the mechanical alloying reduces the adhesive trend of the composites. In aluminum matrix composites, the soft matrix is easily deformed to form scraps and transfers to the counter-faces, so adhesive and micro-cutting wear mechanism exists during the wear process.

Fig. 12. SEM photographs of worn surfaces of (a) Al-Cu-Mg, (b) Al-Cu-Mg (MA), (c) 9%SiCp/Al-Cu-Mg, (d) 9%SiCp/Al-Cu-Mg (MA).

Fig. 12 reveals that the wear tracks on the four different samples differ from each other in agreement with their mechanical properties. The matrix alloy prepared by hand mixing process has the widest wear tracks, see Fig. 12a, and that of the composite prepared by hand mixing

Fig. 13. SEM photographs of pin surfaces (a) Al-4wt%Cu-0.8 wt%Mg, (b) 9%SiCp/Al-4wt%Cu-0.8 wt%Mg, (c) MA 9%SiCp/.

The energy dispersive spectrum (EDS) analysis of the mass transferred on the pin surfaces are shown in Table 2. Among of the all elements on the pin surface, Al, Cu and Si are transferred from the specimens; Fe and Cr are original elements in the pin. The greater is the iron content, the smaller the area of the pin surface coated by the transferred mass from the specimen. Seen form Table 2,

the mass transferred from the matrix alloy is the most and that transferred from the MA 9Vf%SiCp/Al-Cu-Mg composite is the least, which is coinciding with their mechanical properties and the wear rates. The wear behaviors confirm that MA technology improves the mechanical properties of the composites.

Table 2. EDS analysis of the transferred mass on the contacting pin of the specimens (atom %).

Specimens	Elements					Total
	Al	Cu	Si	Fe	Cr	
9%SiCp/Al-Cu-Mg	82.95	3.35	3.65	10.04	-	99.99
9%SiCp/Al-Cu-Mg (MA)	76.17	0.62	1.70	21.08	0.43	100.01
PM Al-Cu-Mg	86.23	3.88	0	9.89	--	100

4. Conclusion

The composites have better mechanical and tribological properties than the matrix alloy and the 9Vf% SiCp/Al-4wt% Cu-0.8wt% Mg composite has the optimum mechanical properties and wear performances, such as, highest strength, lowest wear rate and lowest coefficient.

Mechanical alloying further improves the mechanical properties of the composites, and shifts the optimal magnesium content from 1.2 % mixed by hand to 0.8 % mixed by MA in the matrix content. However, mechanical alloying hardly affects the wear rates and slightly improves its friction coefficients.

SEM photographs indicate that the dominant wear mechanism of the composite is a combination of abrasive and adhesive wear mechanisms, and mechanical alloying reduces the abrasive wear trend of the composites.

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