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Effect of nano-silver on microstructure, mechanical and tribological properties of cast 6061 aluminum alloy

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Abstract: Al6061 matrix with different amounts of nano-silver (1% and 2%) was produced by stir-casting method. Produced samples were characterized by hardness, tensile, compression and wear tests. The hardness of the specimens at room temperature was measured by Brinnell hardness testing machine. The magnitude of hardness increased evidently with the function of the mass fraction of the nano-Ag particle. The polished specimens were examined with an optical microscope. The fracture surfaces of tensile and compressive specimens were further examined by scanning electron microscopy. Wear mechanisms were discussed based on the scanning electron microscopy observations of worn surface and wear debris morphology. There is an increase in compressive strength, ultimate tensile strength, elongation and wear resistance of the Al−Ag composites compared with base alloy. The execution of stir-casting technique is relatively homogenous and fine microstructure which improves the addition of reinforcement material in the molten metal. The results show that Al6061−nano-silver which is the best combination of hardness can replace the conventional material for better performance and longer life.

Key words: Al6061 alloy; nano silver; stir casting; mechanical properties; tribological properties

1 Introduction

Aluminium and aluminium alloys are gaining huge industrial significance because of their outstanding combination of mechanical, physical and tribological properties over the base alloys [1]. Al6061 alloys have been paid increasing attention in the application in the field of structural, automobile and aerospace industries, for its high strength, good heat and good resistance [2]. The influences of alloying (major elements such as Si, Cu, Mg, Ni, Sn, Ti, B, Sr, Be, Mn, Yb, Cr, Zr, Fe, Zn, Ce and Li) on microstructures and mechanical properties of aluminium alloys are evaluated and reviewed [3−8]. Aluminum alloys 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. In recent centuries, among all the Al alloys, Al6061 alloys have been increased much attraction as a matrix material to prepare MMCs owing to their excellent mechanical properties and good corrosion resistance. They are used in the heat-treated condition in which an optimal ratio of physical and mechanical properties is obtained. It solidifies in a broad temperature interval and is suitable for the treatment in the semi-solid state as well as as-cast condition [7,8].

Silver has special properties that make it a very useful and precious metal. It has unique optical, electrical, and thermal properties and is being incorporated into products that range from photovoltaics to biological and chemical sensors [9,10]. An increasingly common application is the use of silver particles for antimicrobial coatings, and many textiles, keyboards, wound dressings, and biomedical devices now contain silver nano-particles that continuously

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release a low level of silver ions to provide protection against bacteria [11]. The additions of Ag to Al−Cu−Mg alloys promote the precipitation of finely dispersed plates of the orthorhombic Ω phase with the {111} α habit plane [12].

An element with a fine and uniform dispersion of particles in the range of 10 nm−1 μm is referred to as "nano-alloying element". Mechanical properties of aluminum alloys such as strength and ductility may be improved, simultaneously if the dispersed particles are of nano-size [13]. The improvement in the mechanical properties of aluminum alloys at room and elevated temperatures strongly depends on the size, shape and distribution of the alloying element in the matrix. At present, a number of techniques are available for the production of micron-sized alloying element [14]. Stir casting and powder metallurgy techniques have been commercially used for production of aluminum alloys [15]. Stir casting is a primary process of alloys and composite production in which continuous stirring of molten base metal is done followed by introduction of alloying element and reinforcements [16]. The various advantages of stir casting are simplicity, flexibility, applicability to large quantity, near net shaping, lower cost of processing and easier control of the matrix structure [17]. High homogeneity is required to attain optimum mechanical properties for the alloying/ composite material [18,19]. Stir casting offers better matrix particle bonding due to stirring action of particles into the melts by selecting appropriate processing parameters, such as stirring speed, time, and temperature of molten metal, preheating temperature of mould and uniform feed rate of particles [20]. The porosity level of composite should be minimized and the chemical reaction between the reinforcement and matrix should be avoided [21,22].

The earlier studies clearly explained the strong interaction between the load and sliding distance as the cause for the wear of a material [23,24]. The study pertains to examine the sliding wear behaviour of composites at different sliding speeds over a range of applied loads and distances. The sliding load and distance are noted with a positive influence on wear with increase of either load or sliding distance or both. But speed shows a negative influence on wear, indicating decrease of wear with increase of speed. RAVINDRAN et al [25] and NARAYANASAMY et al [26] have also reported higher values of coefficient of friction of AMCs as compared to the base alloy. Tribological properties of a sliding system for the materials depend on the properties of the specimen materials, counterfeit materials and their interaction with the environment as well as the experimental conditions, including the applied load and sliding velocity. The wear resistance is mostly influenced by the reinforcement size, volume percentage, load, sliding speed and sliding distance [26]. There are excellent reviews on the tribological properties of aluminum alloys in which these composites are subjected to sliding type of wear with the counter bodies. It is noted that wear of the composites is generally a function of the matrix structure, the processing route, heat treatment as well as the porosity content, particle matrix bonding, reinforcement volume fraction, particle size, and the shape and nature of the reinforcing phase [27].

As a result, during the last decades, there has been a considerable interest in using aluminum alloys in the industry. However, no reference could be found in the literature relating to aluminum alloyed with nano-silver particles, although these alloys are very hopeful for improving the mechanical properties of aluminum alloy. It is tremendously demanding for the traditional mechanical stirring technique to dispense nano-size particles uniformly in Al6061 melts because of the poor wettability and high specific surface areas of nano-Ag particles which lead to agglomeration and particle clustering. In this study, the effects of the addition of Ag on the microstructure, mechanical and tribological properties of the Al6061 alloy were examined.

2 Materials and fabrication

This work is concerned with the study of nano-Ag incorporated aluminum alloy produced by the stir-casting method. The matrix material utilized in this study is Al6061. This alloy is best suited for mass production of lightweight metal castings. Al6061 alloy has copious reimbursement like formability, weldability, wear resistance, corrosion resistance and inexpensive. Al 6061 is available through M/s Coimbatore metal mart, Tamilnadu, India. The chemical composition of Al6061 alloy is given in Table 1. Silver is lustrous, soft, awfully ductile and malleable, which is an excellent conductor of heat and electricity, and can endure extreme temperatures. Nano-silver (Ag) of 60−100 nm in size used for this study was supplied by NaBond Technologies Co., Ltd., China. Table 2 lists the properties of matrix and reinforcing material.

Morphologies of the as-received Al6061 ingots and nano-silver powders were observed by scanning electron microscopy (Fig. 1(a)). The morphology of as-received Ag particles is shown in Fig. 1(b). The size distribution of the nano-Ag particles was measured by particle size

Table 1 Chemical composition of Al6061 (mass fraction, %)

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0.62	0.23	0.22	0.03	0.84	0.22	0.1	0.1	Bal.

Table 2 Properties of Al6061 and Ag

Material	Elastic modulus/GPa	Density/($g\cdot mL^{-1}$)	Poisson ratio	Hardness (HB500)	Tensile strength/MPa	Melting point/°C	Boiling point/°C
Al6061	70−80	2.7	0.33	95	310	652	2519
Ag	72−76	10.49	0.37	206	360	962	2212

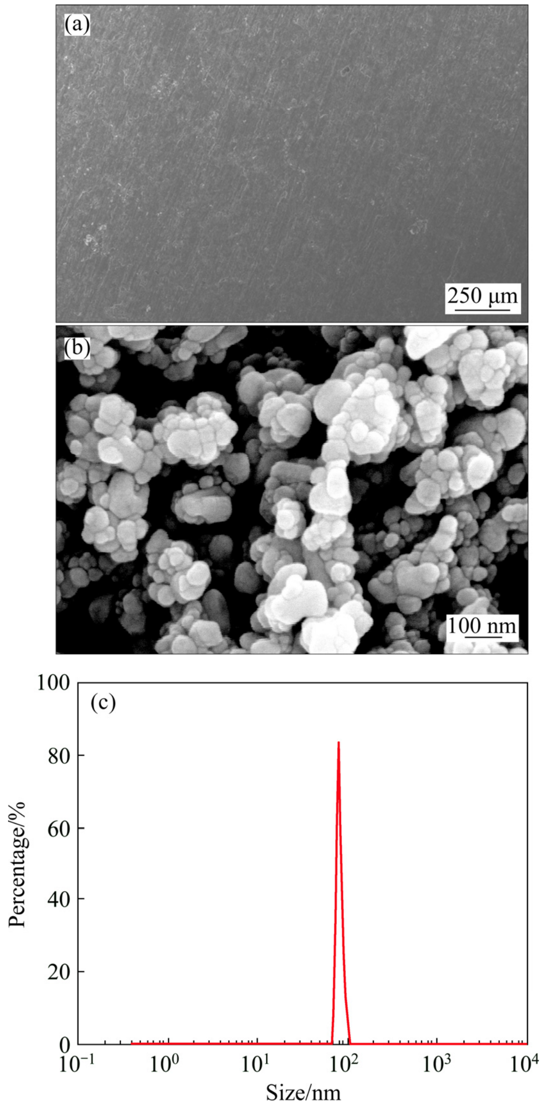

Fig. 1 SEM images of polished Al6061 ingot (a) and nano-Ag particles (b), and particle size distribution of nano-Ag particles (c)

analyzer. The result is shown in Fig. 1(c) and the average size of Ag nano-particles is 80 nm.

Nano-Ag particles were washed by using ultraviolent vibrator with a heater setup with distilled water subsequently with acetone at 50 °C for 1 h. For drying of the washed powders, they were preheated in an air oven at 120 °C for 1 h. The crucible was charged with Al6061 matrix material and it was kept in the stir casting furnace. Figure 2 shows a schematic illustration of the stir casting setup. Al6061 ingot was melted at 710 °C for 30 min. However, there are some problems associated with stir casting of Al6061, such as poor wettability and heterogeneous distribution. Poor wettability of reinforcement in the melt means that the molten Al6061 cannot wet the surface of reinforcement particles. The wettability of Ag particles in Al6061 is enhanced by adding 1% Mg into the Al6061 melt [15]. Mechanical stirring was carried out at a constant speed of 550 r/min, 760 °C for 20 min for entire attempt to obtain heterogeneous distribution of the reinforcement material by the use of alumina-coated stainless steel stirrer (Fig. 2). Finally, the nano-Ag particles were added into Al6061, and after degassing, the melt was cast in the desired preheated molds with the temperature of 250 °C. After that the solidified casting was detached from the mold. The subsequent tests were carried out on the samples to identify their mechanical as well as tribological properties.

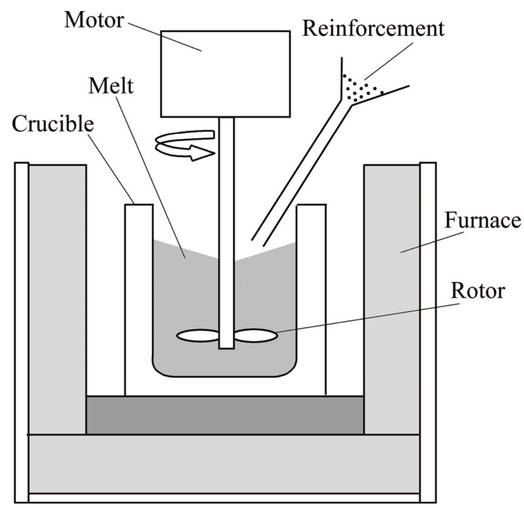

Fig. 2 Schematic illustration of stir casting setup

3 Experimental

After solidification, the samples were machined and tested to find various mechanical properties like hardness, tensile, compressive and wear test according to as-cast ASTM standards. Figure 3(a) shows the samples of 25 mm in diameter and 200 mm in height. Figure 3(b) shows the polished microscopic samples. Figures 3(c) and (d) show the compressive and tensile test specimens respectively. Figure 3(e) shows the wear test specimens.

3.1 Microstructure characterization

The microstructure is also a very significant

Fig. 3 Photographic images of samples (a), polished microscopic and hardness samples (b), compressive test specimens (c), tensile test specimens (d) and wear test specimens (e)

parameter which influences the properties of the Al6061−Ag composite. Specimens were prepared from the casting samples to characterize the microstructure. The ends of the specimens were sequentially polished with abrasive paper of grades 600, 800, 1000 and 2500 conventionally and final polishing was done using 1 μm diamond paste suspended in distilled water in order to obtain mirror-like surface finish. The matrix structure was observed by microscopic examination on specimens after etching using Keller and Weck reagents. Figure 4 shows photomicrographs for the matrix grain structure of Al6061 with 0, 1% and 2% Ag. Figure 4(a) shows the optical micrograph of Al6061 alloy. The Ag particles were found within the grain interior as well as along the grain boundaries of the Al6061 alloy (Figs. 4(b) and (c)). In Figs. 4(b) and (c), the uniform distribution of nano-Ag particles within the Al6061 appeared. A large number of nano-sized Ag particles were uniformly dispersed in Al6061 alloy.

3.2 Density and hardness test

The Archimedes technique was used to measure the density of samples according to the ASTM: B962−13. The density of the samples was dogged by a high precision digital electronic weighing balance with an accuracy of 0.01 mg. The Brinell hardness testing machine is a device that indicates the hardness of a material, usually by measuring the effect on its surface of a localized penetration by a standardized rounded or pointed indenter. The Brinell hardness was measured on the polished samples using a ball with 2.5 mm in diameter at a load of 10 kg. For each specimen, a minimum of five tests was carried out to obtain repeatable values.

3.3 Tensile and compressive test

The composites with different mass fractions of nano-Ag particles were tested for uniaxial compressive strength. Specimens with aspect ratio of 2:1 (ASTM E9−89a) were affianced from cast samples to assess the compressive properties, using an Instron servo-hydraulic test machine (model 8500).

The specimen was prepared as per ASTM: E8/E8M−13a standard. The tensile tests were performed using a universal testing machine at room temperature as per the standard and the average ultimate tensile strength; yield strength (The stress of a material can withstand without permanent deformation) and elongation were reported for each specimen.

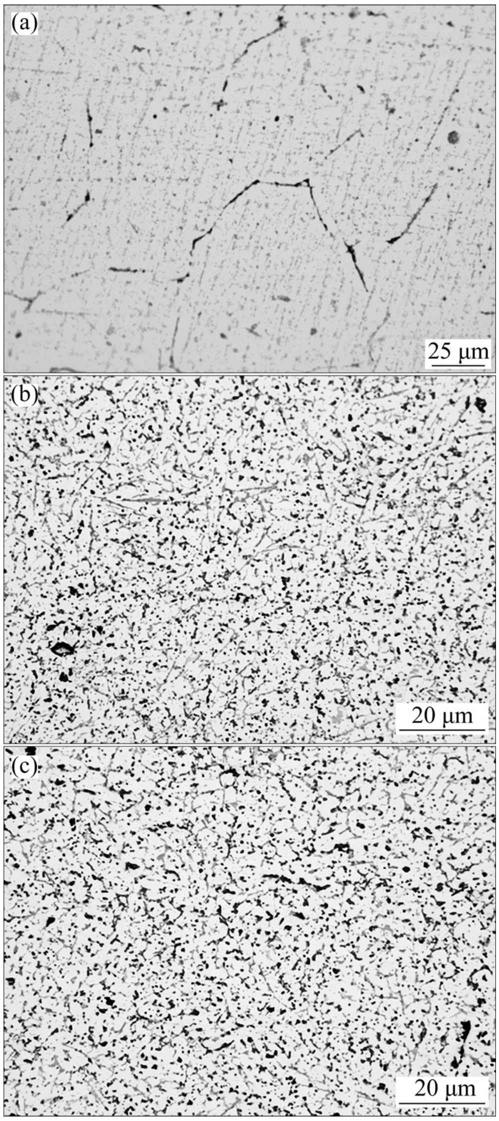

Fig. 4 Optical micrographs of samples: (a) Al6061; (b) Al6061−1%Ag; (c) Al6061−2%Ag

3.4 Sliding wear tests

Friction and wear properties of the samples were investigated using a pin-on-disk wear test machine according to the ASTM G99−05 standard. The specimens of 10 mm in diameter and 30 mm in length were cut from the cast composite. After each test, the specimen and counter face disc were cleaned with organic solvents to remove traces. The specimen was weighed before and after wear testing to an accuracy of 0.01 mg to determine the amount of wear loss. Mass loss data were converted into volume loss with respect to their respected density. The wear volume loss has been converted to specific wear rate. It is the ratio of wear volume loss to the multiplication of sliding load and distance. The coefficient of friction was determined from the applied normal load and the frictional/tangential load obtained from the strain gauges. It was calculated from the recorded frictional load and applied normal load. Each test was repeated three times, and the average values were taken. The tests were conducted at room temperature and a sliding speed of 2 m/s under an applied load of 20 N and dry sliding condition.

4 Results and discussion

4.1 Mechanical properties

The results of density tests of consolidated Al6061−nano-silver composite and Al6061 are shown in Fig. 5(a). The density is improved with increasing the mass fraction of the Ag nano-particles. Figure 5(b) shows the variation of hardness of the Al6061 with increasing Ag content. The average hardness values of Al6061, Al6061−1%Ag and Al6061−2%Ag samples were measured to be BHN 92, BHN 96 and BHN 98, respectively. These obtained hardness values for Al6061−Ag composite samples are significantly higher than those for Al6061 (BHN 92). It can be understood from Fig. 5(b) that the hardness of the composites was improved with the increase in mass fraction of nano-Ag particles.

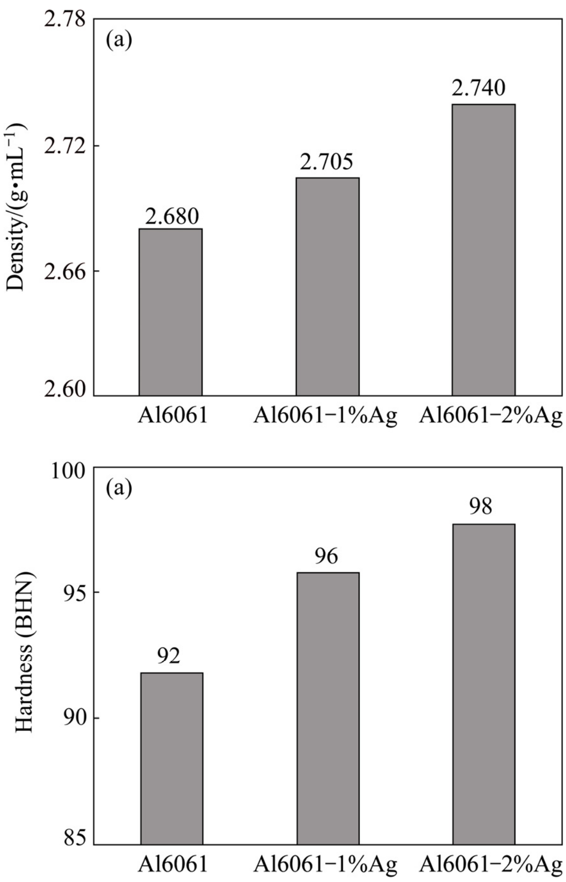

Fig. 5 Density (a) and hardness (b) of samples

4.2 Compressive and tensile properties

The effect of addition of nano-Ag particles taken with Al6061 matrix alloy on its compressive strength is shown in Table 3. A significant variation in the entire mass fraction of the Al6061 was also examined. The compressive strength increases with an increase in the addition of nano-Ag. For better understanding of the compressive behaviour of the mechanical response of Al6061−Ag composites, the SEM images of the fracture surfaces of the specimens tested were captured.

Table 3 Compressive strength of Al6061−nano-Ag-composite

Sample	Ultimate compressive strength/MPa
Al6061	142
Al6061−1%Ag	158
Al6061−2%Ag	174

Figure 6(a) shows the compressive fractographs of the cast Al6061 matrix. Al6061 matrix does not offer any mechanism to stop or retard the propagating crack and therefore may be the reason behind the reduction in fracture. Figures 6(b) and (c) show the compressive fractographs of the cast Al6061−Ag composites. The fracture of Al6061−Ag composites is comprised of ductile modes of fracture. It can be pragmatic that the matrix and reinforcing phase have failed in a ductile manner with cleavage faces across the path of the crack. No evidence of brittle break, which is a display of the formation of large contact between metal–metal during testing, is seen. The random distribution of nano-Ag causes significant improvement in elastic modulus which amends the tying potency to the Al6061. The results divulge that the yield strength, ultimate strength and fracture strength of the composites have increased in comparison with those of the pure Al6061.

Figure 7 demonstrates that the yield strength, ultimate tensile strength and elongation of as-cast Al6061 alloy and Al6061−nano-Ag composites. It can be seen that the ultimate tensile strength and yield strength of the composites are simultaneously enhanced compared with those of as-cast Al6061. Also, it can be observed that elongation increases with the increasing mass fraction of Ag nano-particles. Figure 7 shows the effect of Ag content on the ductility of cast Al6061−Ag composites (measured in terms of elongation). It can be seen from

Fig. 7 that the ductility of the alloys increases notably with the increase in Ag content. The increase in ductility in comparison with the matrix alloy is the most commonly encountered the soft and ductile nature of Ag. The rise in ductility can be ascribed to the incidence of a soft nano-silver reinforcing phase in Al6061 alloy.

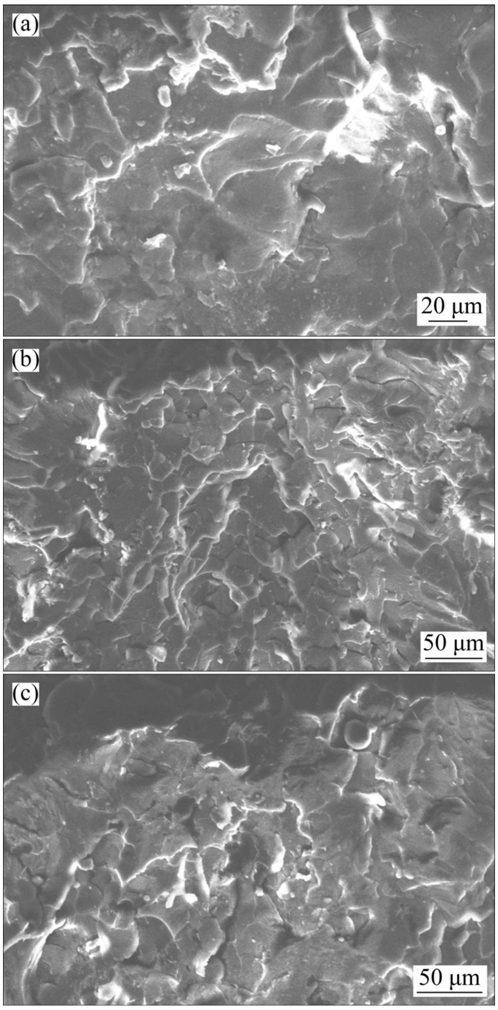

Fig. 6 Compressive fractographs of specimens: (a) Al6061; (b) Al6061−1% nano-Ag; (c) Al6061−2% nano-Ag

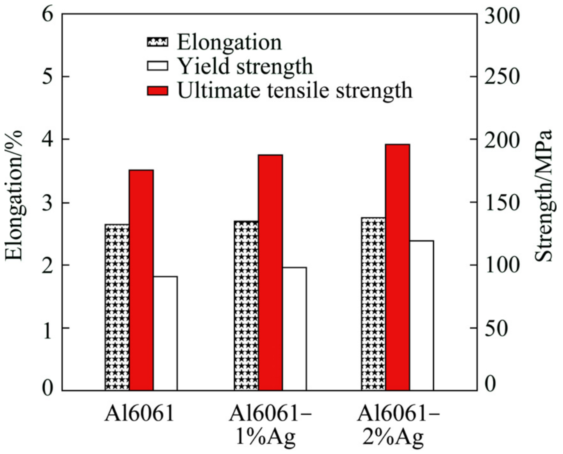

Fig. 7 Tensile properties of cast samples

A scanning electron microscope was used to investigate the fracture surfaces of the Al6061−nano-Ag composite, as well as the status of Ag reinforcing percentage within the Al6061. Fractographs were analyzed to determine the mode of failure. Figure 8 shows the tensile fractographs of the cast specimen. Figure 8(a) shows that Al6061 is leading to a relatively flat fracture surface involving a separate cleavage pattern and dimpled features are observed on fracture surface in Al6061. However, some areas of the Ag composite fracture surfaces consist of dimples which may be a result of the void nucleation and subsequent coalescence by strong shear deformation and fracture process on the shear plane. Figure 8(b) shows the evidence for the presence of dimples and smack within the Al6061 matrix in the presence of 1% nano-Ag particles. Figure 8(c) shows dislocations trapped by Ag nano-particles. This type of fracture occurs as a result of micro-void formation and coalescence. This will lead to increase in the tensile strength of the Al6061 alloy during tensile tests.

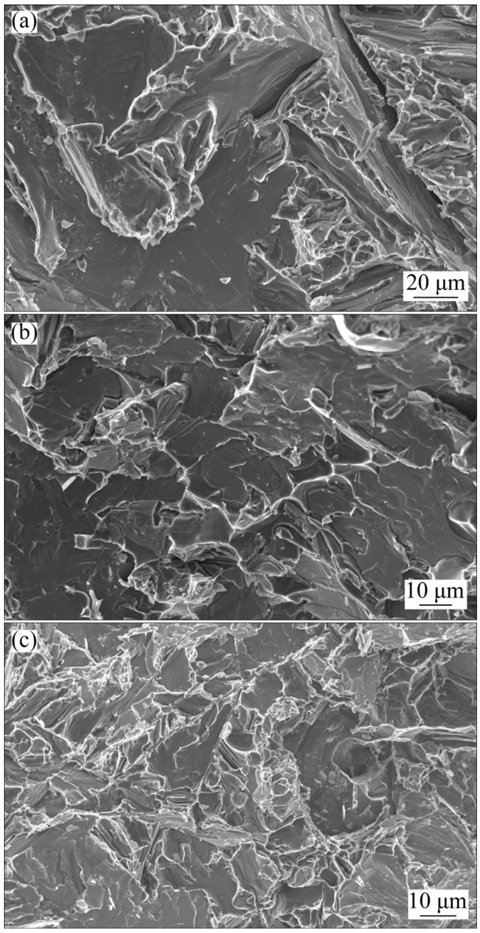

Fig. 8 Tensile fractographs of specimens: (a) Al6061; (b) Al6061−1% nano-Ag; (c) Al6061−2% nano-Ag

4.3 Sliding wear behavior

4.3.1 Specific wear rate and friction coefficient

It is realistic that the specific wear rate of the Ag composite decreases with the addition of nano-Ag particle in the Al6061 matrix alloy. However, for particular content, the Al6061−nano-Ag composite have lower specific wear rate than the cast Al6061 alloy. Dry friction and wear performance of the Al6061−nano- Ag composite and Al6061 alloy at room temperature were studied by using a pin-on-disk wear testing machine. The specific wear rate and friction coefficient has been studied as function of the mass fraction of the nano-silver particles, load, sliding distance and sliding velocity. The results show that the specific wear rate of the test specimens decreases with the increasing mass fraction of Ag, as shown in Fig. 9. Also, the coefficient of friction of specimen increases with the increasing mass fraction of Ag element, as shown in Fig. 10.

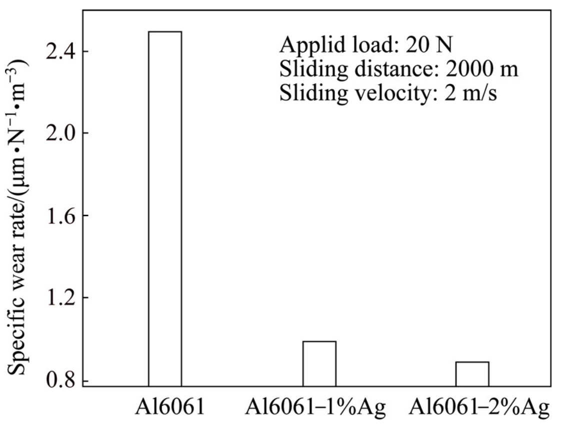

Fig. 9 Variation of specific wear rate of Al6061 and Al6061−nano-Ag composites

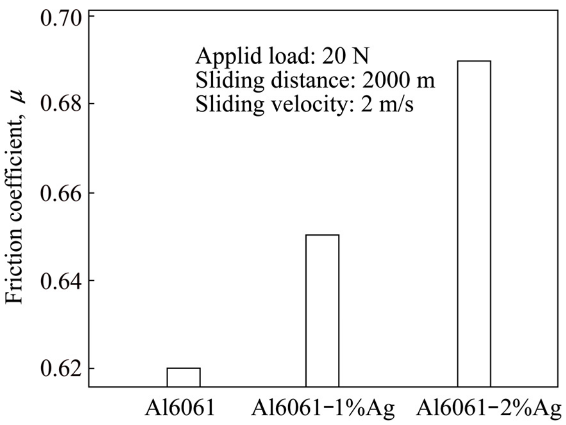

Fig. 10 Variation of coefficient of friction of Al6061 and Al6061−nano-Ag composites

4.3.2 Worn surface morphology

Figure 11 shows the SEM images of worn surfaces of cast Al6061 alloy and its nano-Ag composites at an applied load of 20 N and sliding distance of 2000 m. From Fig. 11(a), it is clearly seen wide grooves on the worn surface due to abrasive wear, as a result, in severe plastic deformation of the worn surface in the sliding direction and for this reason the wear loss is high in Al6061. Figure 11(b) shows the worn surface of Al6061−1% nano-Ag composite at 20 N. A slight ploughing can be observed. Evaluating with Al6061, a smooth worn surface was obtained by adding nano-Ag particles in Al6061. This is believed to be the result of abrasion by bonding nano-Ag particles and Al6061. The material delamination is not severe on the Al6061−2% nano-Ag composite (Fig. 11(c)), namely, the grooves are fine.

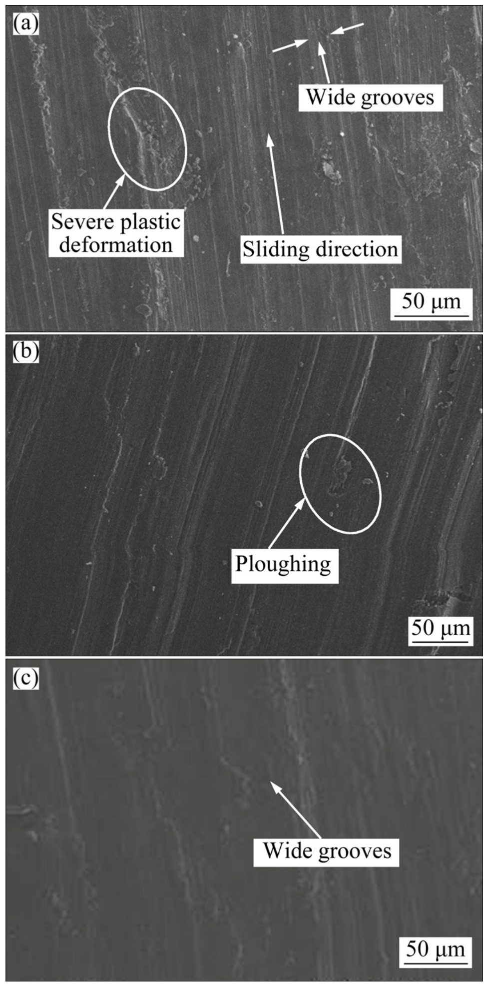

Fig. 11 SEM images of worn surfaces of Al6061(a), Al6061−1% nano-Ag (b) and Al6061−2% nano-Ag (c) alloys

4.3.3 Wear debris morphology

Chip can be collected by allowing it to fall on a glass slide. The microstructures of the chips of Al6061−nano-Ag composites were carried out by SEM. Figure 12 shows the SEM images of the chips of Al6061, Al6061−1% nano-Ag and Al6061−2% nano-Ag at a normal load 20 N. The wear debris particles observed in Fig. 12(a) are large and shaped-like thin sheets. However, the chips of the Al6061−nano-Ag composite consist of a combination of fine and coarse powders with irregular shapes. Figures 12(b) and (c) show that with the addition of the nano-Ag, the size of chip is also abridged, due to the effect of Ag content and its acquaintance with Al6061. The Al6061−2% nano-Ag composite has smaller chips than with 1% nano-Ag.

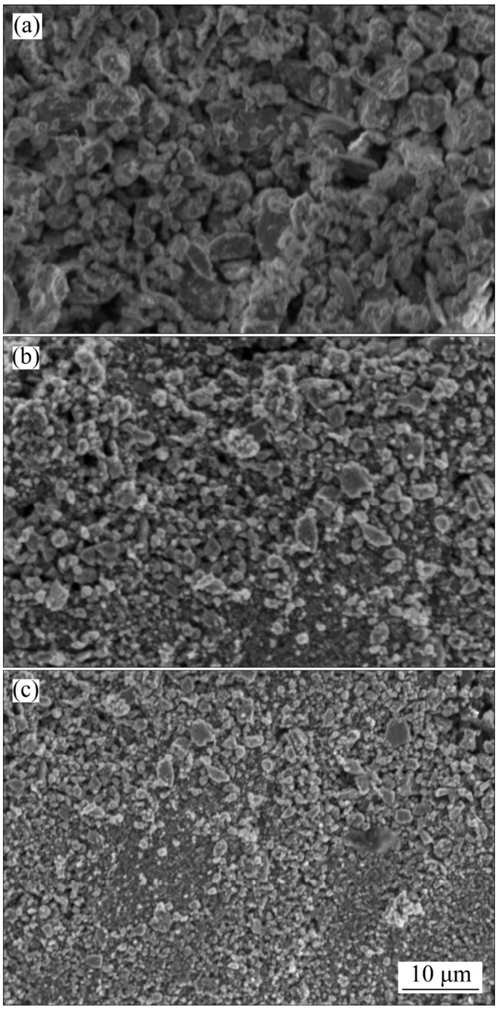

Fig. 12 SEM images of wear debris of Al6061 (a), Al6061−1% nano-Ag (b) and Al6061−2% nano-Ag (c)

5 Conclusions

Compared with the conventional aluminum alloy, Al6061−nano-Ag composites exhibit excellent mechanical properties and wear resistance. The obtained composites have fine grain microstructure, realistic Ag nanoparticles distribution in the Al6061, having low porosity. It is revealed that the hardness and density of Al6061−nano-Ag composite samples increase with increasing the mass fraction of nano-Ag particles. The reinforcement particles enhance the hardness of Al6061 and Al6061−nano-Ag composites from BHN 92 to BHN 98. With increasing in nano-Ag, the compressive strength and ultimate tensile strength show an increasing trend. The results also show that the compressive strength and tensile strength of Al6061−nano-Ag composite are greater than those of Al6061. Deformation behaviour is explained in terms of SEM observations of the fractured surfaces of compressive and tensile specimens and the worn surfaces. It is concluded that the wear resistance of the reinforced composites increases with increasing the nano-Ag within the range studied. The wear rate results of the unreinforced alloy and reinforced composites show severe and mild wear rate regimes. Coefficient of friction of Al6061 alloy increases with the addition of nano-Ag particles.

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纳米银对铸态 6061 铝合金的组织、力学和摩擦性能的影响

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摘　要：利用搅拌铸造法制备不同含量纳米银(1%，2%)6061 铝基合金，采用硬度、拉伸、压缩和磨损实验表征所制备的试样，并用布氏硬度试验机测试样品的室温硬度。随着合金化元素质量分数的增加，硬度明显增大。采用光学显微镜检测抛光样品，通过扫描电子显微镜进一步研究拉伸和压缩试件的断裂表面。与基体合金相比，铝−银合金的抗压强度、极限抗拉强度、伸长率和耐磨性有所提高。采用搅拌铸造技术得到了相对均匀和精细的组织，提高了熔融金属中增强材料的添加量。结果表明，最佳硬度组合 6061 铝−纳米银合金可取代传统材料，获得更优的性能和较长的寿命。

关键词：6061 铝合金；纳米银；搅拌铸造；力学性能；摩擦性能

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