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Effect of $ZrSiO_4$ particles on the wear properties of as-cast Al matrix particulate composites fabricated via various casting routes

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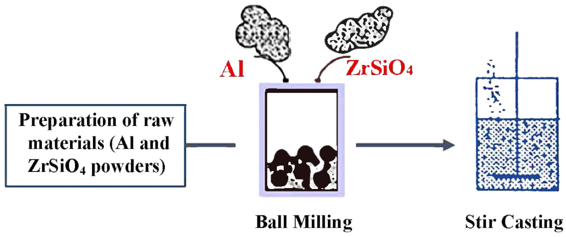
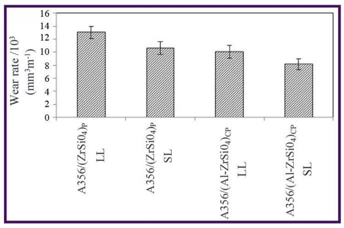
HIGHLIGHTS

- Al-A356/$ZrSiO_4$ composites were fabricated by two different routes.
- The distribution of particles was improved within the matrix in the semisolid state.
- The wear properties were enhanced in the A356/(Al-$ZrSiO_4$)$_{cp}$-SL specimen.

GRAPHICAL ABSTRACT





Wear rate of the fabricated composites

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ABSTRACT

This study deals with the effects of $ZrSiO_4$ particles addition on the abrasive wear behavior of aluminum based metal matrix composites. The Al-A356/5 vol% $ZrSiO_4$ specimens were prepared by the injection of particles in the as-received form or Al-$ZrSiO_4$ milled composite powder. The injection of composite powder caused remarkable improvement in $ZrSiO_4$ distribution within the Al-356 matrix alloy. The composites were fabricated by two different routes: semisolid-liquid state (SL) and liquid-liquid state (LL). According to the results, a better distribution of reinforcing particles was observed when the stirring was conducted in the semisolid state. Based on the wear test results, the composite with ball-milled Al-$ZrSiO_4$ particles (A356/(Al-$ZrSiO_4$)$_{cp}$) processed in the SL state exhibited the highest wear resistance in terms of wear rate and friction coefficient. The worn surfaces of specimens were examined to identify the possible mechanisms.

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1. Introduction

In recent years researchers have begun an intensive study of the effects of particle reinforcement on the mechanical properties of metals and their alloys, this reinforement combines the ductility of metals with the high temperature stability of hard particles to enhance the properties of metals [1,2]. Because of its industrial application, pure aluminum and its alloys have been considered as some of the most interesting matrix constituents for the preparation of metal matrix composites [3,4]. The selection of matrix alloy, reinforcing particles, and the fabrication methods are the key factors that influence the microstructure and mechanical properties of the Al-based composites [5,6]. Nowadays, intensive research has focused on the kinks in particles, which are used for the reinforcement of the matrix. Various kinds of particles such as Al_2O_3 [7], TiB_2 [8], TiC [9], SiC [10], and carbon nano-tubes (CNTs) [11] have been used as reinforcing parts for Al-based composites, these parts have led to high strength, high stiffness, and wear resistance in comparison to the unreinforced composites. Abbasipour *et al*. [11] studied the microstructure and hardness properties of Al356 aluminum alloy reinforced with CNTs. Their results revealed that the fabrication of composites via stir casting and compocasting routes can refine the microstructure and increases the hardness of composites. Abdizadeh *et al*. [8] investigated the effects of processing temperature on the mechanical behavior of particulate-reinforced composites, and their investigation showed that the processing temperature and a particular kind of reinforcement are able to control the composites' properties. Baradeswaran *et al*. [7] results showed that by increasing Al_2O_3 particles, both tensile and compression increased. Das *et al*. [5] studied the effect of zircon sand particles size on the wear behavior of Al-4.5 wt% Cu alloy matrix composites, their results revealed that smaller particles can improve the wear properties of composites.

$ZrSiO_4$ is one of the reinforcing particles that can be used as a second phase in metal matrix materials [12]. Based on the authors' knowledge, the effects of $ZrSiO_4$ particles on the wear resistance of aluminum has not been comparatively investigated for different casting routes. Because of the incompatibility of particles and liquid metals as well as their differences in densities, several problems can occur in the composite fabrication process. Therefore, the aim of this work is to experimentally study the tribological properties of Al-$ZrSiO_4$ composites with various fabrication techniques. In this work, various methods are introduced which could result in less agglomeration and better distribution of zircon silicate particles in the matrix.

2. Experiments

2.1. Materials

The Al-A356 (supplied by Golpaygan Negin Aluminum Co., Iran) alloy with the nominal chemical composition shown in Table 1 was employed as the matrix alloy. The liquids and solids temperatures of this alloy are 615 and 583 °C, respectively, and its relatively large semisolid interval makes it suitable for semisolid processing.

The commercial Al powder had an average size of 25 µm and the $ZrSiO_4$ powder (supplied by Hebei BaoSiLai Techonology Co., China) had an average size of 1 µm.

2.2. Experimental procedure

$ZrSiO_4$ and Al powders, in the mass ratio of 1, were milled using a planetary ball mill in an Ar atmosphere, with a ball (chromium steel with 10 mm diameter) to powder ratio of 10:1, for various times of 3, 6, and 9 h. The speed was set at 200 rpm.

The 5 vol% $ZrSiO_4$/A356 composites were fabricated by two different routes. In the case of the semisolid-liquid state (SL) process, the A356 alloy was melted in a 3-kg capacity clay-bonded graphite crucible. Two calibrated thermocouples were inserted into the melt and the furnace to measure their temperatures. The temperature was first raised to 750 °C and the melt was stirred at 600 rpm using a graphite impeller attached to a variable speed AC motor. Then, the temperature of the melt was then decreased to about 590 °C by lowering the furnace temperature while stirring was continued. Next, the stirrer was positioned just below the surface of the slurry and a specific quantity of particles was added. Lastly, the impeller was placed near the bottom

Table 1. Chemical composition (wt%) of Al-A356 alloy.

Si	Mg	Mn	Zn	Cu	Fe	Al
6.93	0.38	0.23	0.26	0.25	0.44	Balance

of the crucible and the semisolid slurry was stirred for 10 min to obtain a uniform reinforcement distribution in the matrix. In order to facilitate the casting of slurry, it was heated to 750 °C and stirred at this temperature for another 5 min. In contrast, for the liquid-liquid state (LL) process, the A356 alloy was melted at 750 °C and the powders were added at this state. The stirring was done for 15 min. In the SS and SL routes, $ZrSiO_4$ powder was added in two different forms of ball-milled Al-$ZrSiO_4$:(Al-$ZrSiO_4$)$_{cp}$ or direct addition of $ZrSiO_4$:($ZrSiO_4$)$_p$, respectively.

Dry sliding wear tests were conducted at room temperature using a pin-on-disc machine. The specimens in the form of pins were slid against a steel disk (1.5Cr, 1C, 0.35Mn, 0.25Si) with the hardness of 64 HRC. The sliding velocity and applied load were kept constant at 1 m.s^{-1} and 20 N, respectively. Wear tests were performed for a sliding distance of 200 m. For each alloy, three specimens were tested and the average values were reported. The worn surfaces of specimens were analyzed using a KYKY-EM3900M scanning electron microscope.

3. Results and discussion

3.1. High-energy ball milling

Commercial pure micro-sized aluminum powder and $ZrSiO_4$ particles with a maximum size lower than 200 and 100 μm, respectively, were used for the high energy balling process with a ball to powder ratio of 5:1. Ethanol (10 wt%) was used to avoid agglomeration of the particles and the vials were filled with argon to minimize the oxidation of Al powders during milling. The ball milling experiments were conducted for 3, 6, and 9 h. SEM investigation was performed to evaluate the influence of ball milling time on the evolution of morphology of Al and $ZrSiO_4$ powders. Fig. 1 shows the morphology of Al-5% $ZrSiO_4$ after 3, 6, and 9 h milling. As can be seen, the repetitive deformation changes the aluminum powder particles from roughly spherical to a flake-like shape. Also, $ZrSiO_4$ aggregate particles were broken and dispersed into the metal particles. Therefore, from the microstructure one can see that high-energy ball milling leads to the plastic deformation of Al powder particles. A comparison of microstructural evolution after various times of ball milling shows that an adequate dispersion of $ZrSiO_4$ particles within the matrix was obtained after a milling time of 9 h.

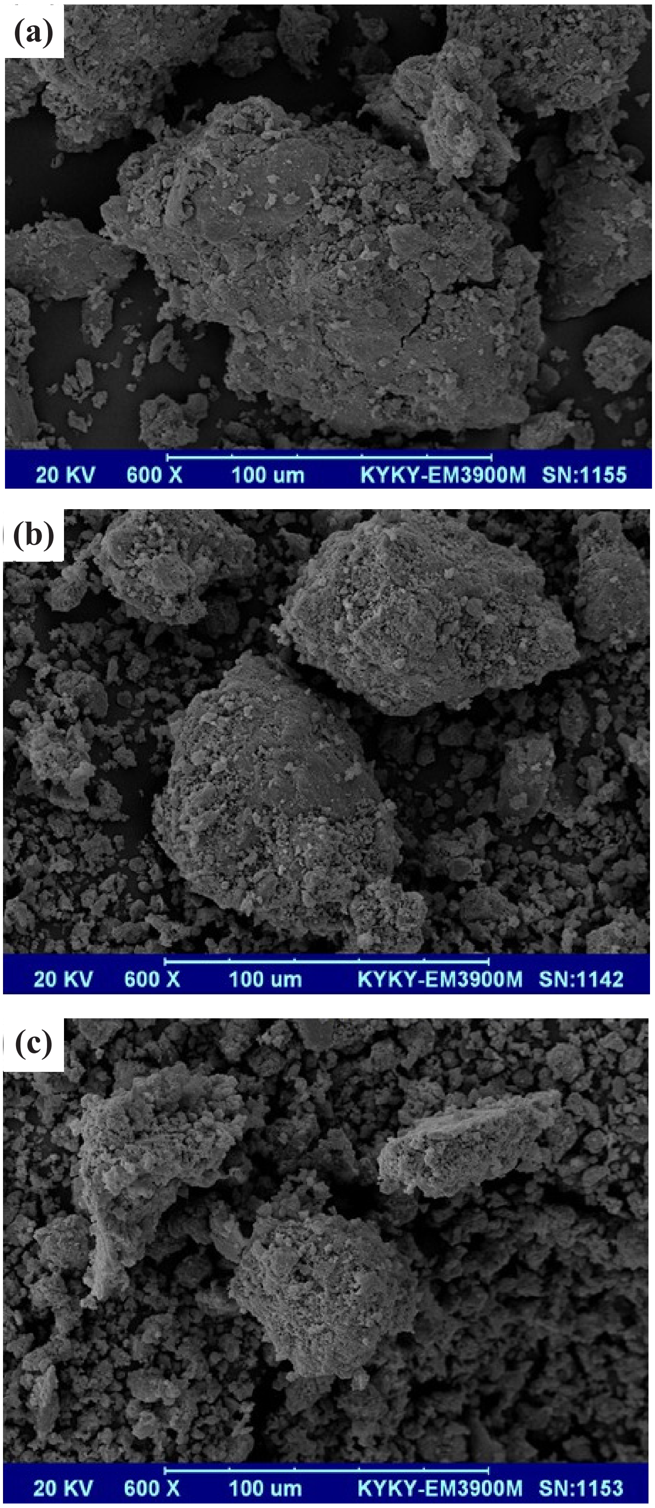

Fig. 1. The SEM micrograph of the Al-5% $ZrSiO_4$ powders after (a) 3 h, (b) 6 h, and (c) 9 h of ball milling.

3.2. Distribution of $ZrSiO_4$ in the matrix

As it is well documented in the literature, the distribution of reinforcing particles in a metallic matrix is a critical factor affecting the various properties of the final composite [13,14]. Fig. 2 shows the Zr elemental X-ray mapping demonstrating the distribution of $ZrSiO_4$ particles within the matrix of Al-A356 alloy cast in the LL and SL states. As it can be seen, the liquid stirring causes the formation of $ZrSiO_4$ agglomerates. On the contrary, when stirring was conducted in the semisolid state, a better distribution of reinforcing particles is observable. This can be attributed to the effect of viscosity. When the stirring is done in the semisolid state, the viscosity of the molten metal is high; as a result, friction between the molten metal and $ZrSiO_4$ particles increases [1]. Due to enhanced friction between the components, the α-Al dendrites are broken and a finer microstructure is obtained. Consequently, a homogeneous distribution of particles can be achieved. The effect of the type of the injected powder on particle distribution is also observable in Fig. 2. One can see, a better distribution of the reinforcing particles has been obtained when the particles were added in the form of milled Al-$ZrSiO_4$ powders. Fig. 2 shows a much better distribution of reinforcement is obtained in the A356/(Al-$ZrSiO_4$)$_{cp}$ composite matrix when the particles were added in the semisolid state.

3.3. Wear test results

Fig. 3 shows variations of the wear rate of the fabricated specimens. As it can be observed in Fig. 3, wear rate of the A356/(Al-$ZrSiO_4$)$_{cp}$ composite processed in the SL state is the lowest. This can be associated to a more uniform distribution of reinforcement than the other specimens (see Fig. 2).

Comparing the wear properties of the specimens, it is seen that the specimen processed with the LL route shows a poorer wear resistance than the specimen processed with the SL technique, regardless of the injection method of reinforcement. This is due to the aggregation and clustering of $ZrSiO_4$ particles, as indicated in Fig. 2. The role of uniformly distributed reinforcing particles on the mechanical properties of Al matrix composites has been also reported by other researchers [1,10].

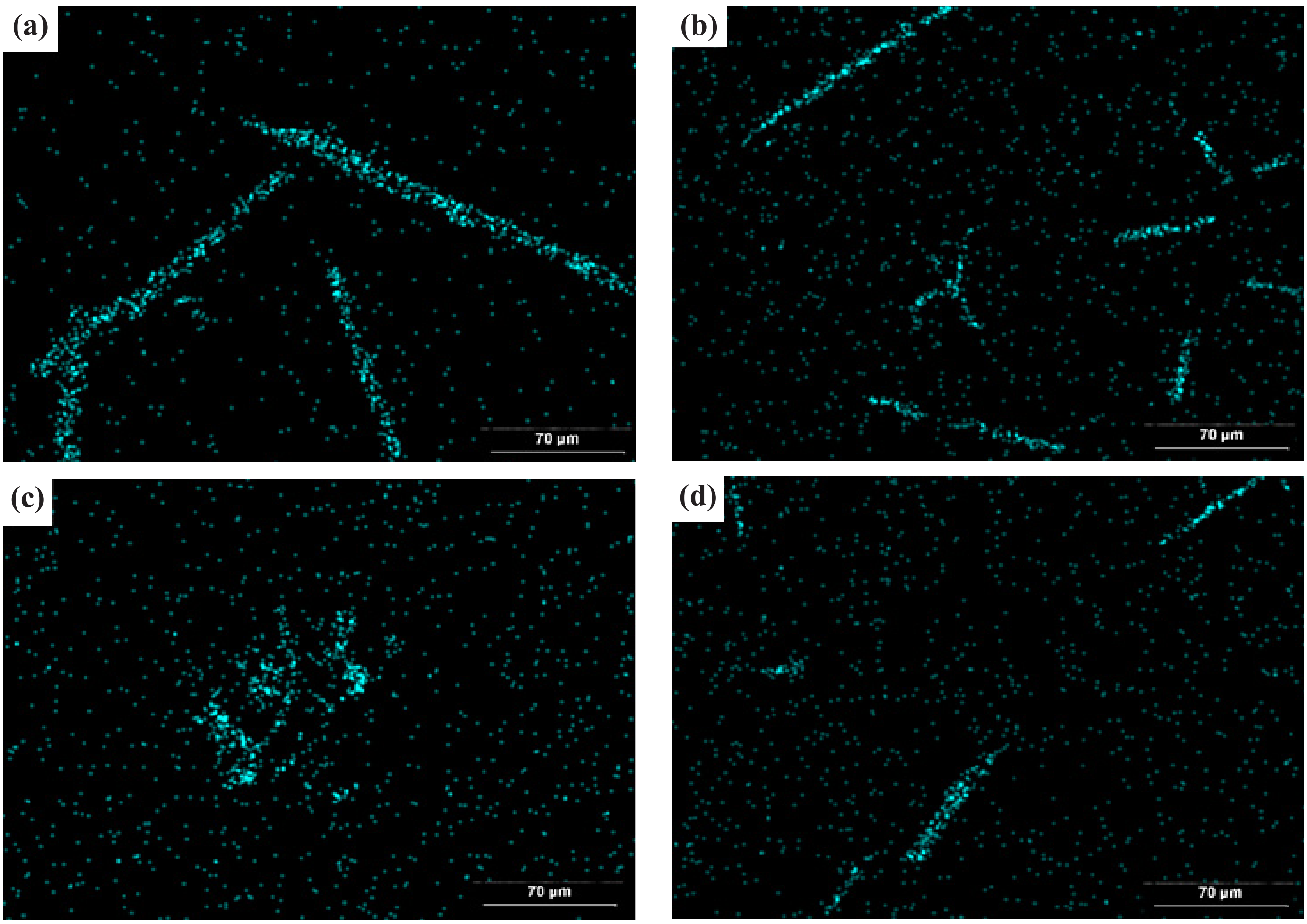

Fig. 2. (a),(c) The x-Ray map of Zr distribution in the matrix of the A356-($ZrSiO_4$)$_p$ composite and (b),(d) the A356-(Al-$ZrSiO_4$)$_{cp}$ composite with the casting method of (a),(b) LL and (c),(d) SL.

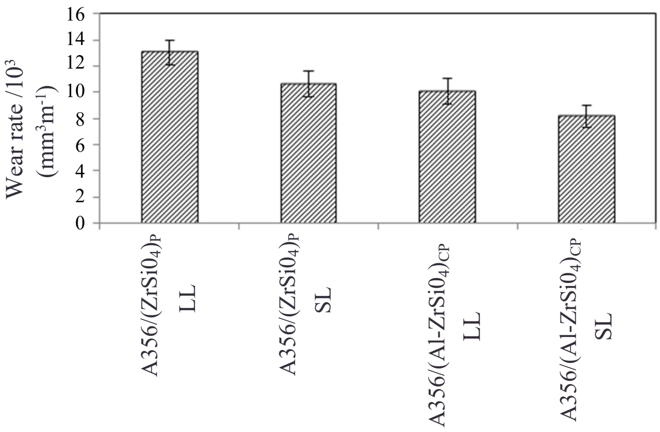

Fig. 3. The variations of the wear rate of the fabricated specimens.

Fig. 4 shows the COF-sliding distance curves for the fabricated specimens. In addition, the values of the mean COF are depicted in Fig. 5. It must be noted that the values of mean COF were obtained by averaging the data in the specimens' COF-sliding distance curves. The trend of mean COF is similar to the wear rate. It can be seen that the A356/(Al-$ZrSiO_4$)$_{cp}$ composite processed in the SL state exhibits the lowest mean COF.

Fig. 6 shows SEM micrographs from the worn surface of the specimens. From Figs. 6(a), 6(b), and 6(c), we see that plastic deformation has occurred during wear tests of the A356/(Al-$ZrSiO_4$)$_p$-LL, A356/(Al-$ZrSiO_4$)$_{cp}$-LL, and A356/(Al-$ZrSiO_4$)$_p$-SL specimens. This was accompanied with deep grooves observed on the worn surface of these specimens. However, plastic deformation was significantly reduced on the worn surface of the A356/(Al-$ZrSiO_4$)$_{cp}$-SL specimen, its worn surface was characterized by localized shallow grooves and very fine scratches (Fig. 6(d)).

4. Conclusion

From this research study, it can be seen that the high strength of metal matrix composites is the result of several strengthening mechanisms, which contribute to wear and mechanical behavior of the final composites. In particular, the strengthening mechanisms for pure metals reinforced with ceramic particles are summarized. High-energy ball milling also induced a strong effect on the metal-matrix microstructure. The large number of defects, likely in the form of dislocations, introduced by the repeated collisions of balls onto the powder particles, led tohigher wear properties. The following results can be drawn from the present work:

1. The addition of milled Al-$ZrSiO_4$ powders resulted in a considerable improvement in the $ZrSiO_4$ distribution within the matrix.

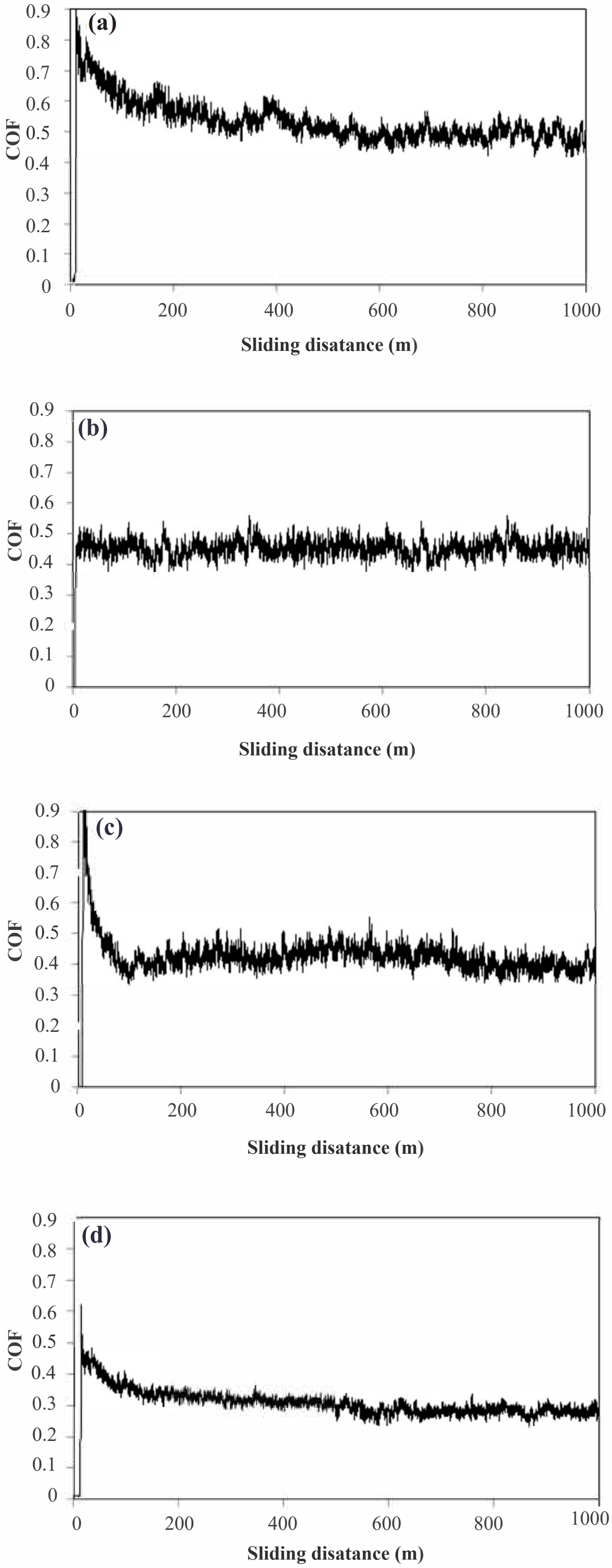

Fig. 4. The COF-sliding distance curves for the fabricated specimens (a) A356/($ZrSiO_4$)$_p$-LL, (b) A356/($ZrSiO_4$)$_p$-SL, (c) A356/($ZrSiO_4$)$_{cp}$-LL, and (d) A356/(Al-$ZrSiO_4$)$_{cp}$-SL.

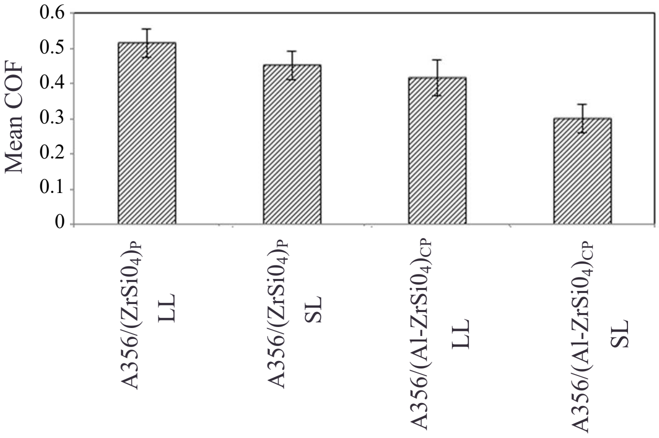

Fig. 5. The variations of the mean COF of the fabricated specimens.

2. A better distribution of the reinforcing particles was observed when the stirring was conducted in the semi-solid state, as compared with the liquid state stirring.

3. The highest wear properties in terms of wear rate and friction coefficient were obtained in the A356/(Al-$ZrSiO_4$)$_{cp}$-SL specimen.

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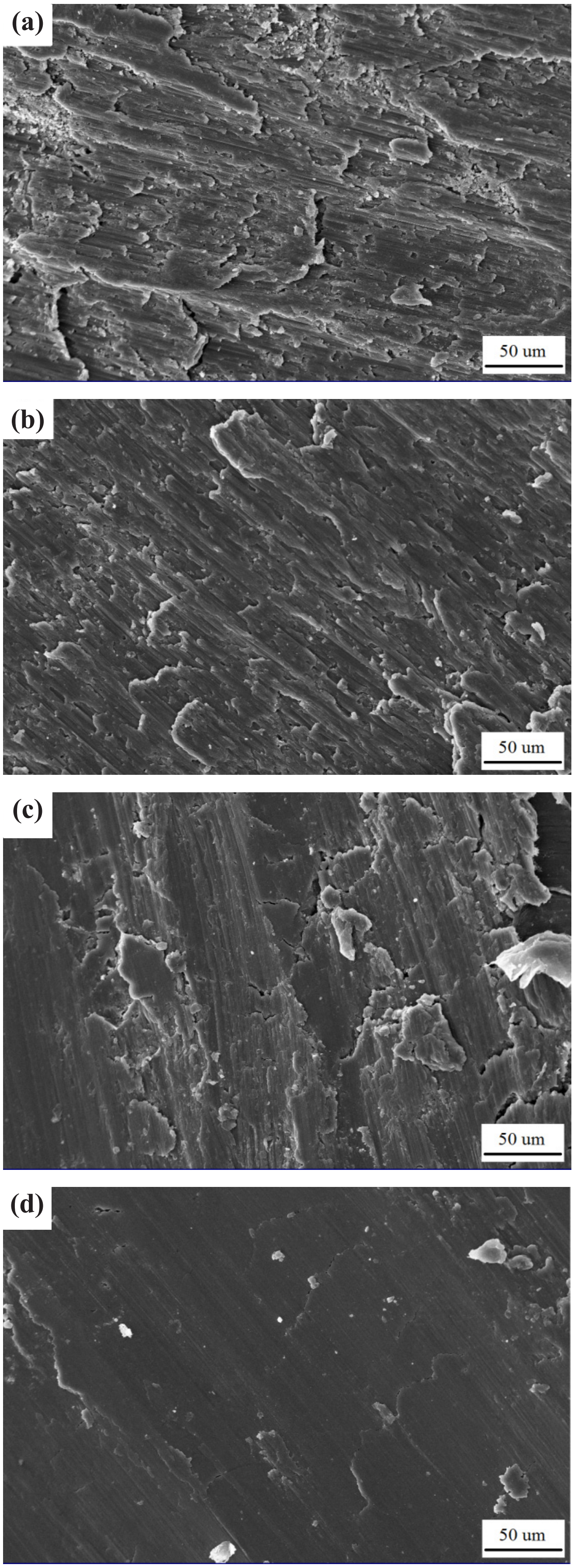

Fig. 6. SEM micrographs from the worn surface of the specimens, (a) A356/($ZrSiO_4$)$_p$-LL, (b) A356/($ZrSiO_4$)$_p$-SL, (c) A356/(Al-Zr-SiO_4)$_{cp}$-LL, and (d) A356/(Al-$ZrSiO_4$)$_{cp}$-SL.

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