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Studies on mechanical and dry sliding wear of Al6061–SiC composites

G.B. Veeresh Kumar [a,*], C.S.P. Rao [b], N. Selvaraj [b]

[a] Department of Mechanical Engineering, Amrita Vishwa Vidyapeetham, Bangalore, India
[b] Department of Mechanical Engineering, National Institute of Technology, Warangal, A.P., India

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ABSTRACT

Particulate reinforced Al-MMCs exhibits better mechanical properties and improved wear resistance over other conventional alloys. In the present paper, the experimental results of the mechanical and tribological properties of Al6061–SiC composites are presented. The composites of Al6061 containing 2–6 wt% SiC were prepared using liquid metallurgy route. The experimental results showed that the density of the composites increase with increased SiC content and agrees with the values obtained through the rule of mixtures. The hardness and ultimate tensile strength of Al6061–SiC composites were found to increase with increased SiC content in the matrix at the cost of reduced ductility. The wear properties of the composites containing SiC were superior to that of the matrix material.

1. Introduction

Metal–matrix composites (MMCs) are being increasingly used in aerospace and automobile industries owing to their enhanced properties such as elastic modulus, hardness, tensile strength, wear resistance combined with significant weight savings over unreinforced alloys [1]. The commonly used metallic matrices include aluminum, magnesium, titanium, and their alloys. These alloys are preferred matrix materials for the production of MMCs. The reinforcements being used are fibers, whiskers and particulates [2]. The advantages of particle-reinforced composites over others are their formability with cost advantage [3]. Further, they have inherent heat and wear resistant properties [4]. Al6061 is a popular choice as a matrix material to prepare MMCs owing to its better formability characteristics and option of modification of the strength of composites by adopting optimal heat treatment. The strength of these composites is proportional to the percentage volume and fineness of the particulates used as reinforcements [5]. These Al-alloy composites which are reinforced with ceramic particulates led to a new generation of tailorable engineering materials with improved specific properties.

Among several series of Al-alloys, heat treatable Al6061 is much explored. Al6061 alloys are highly corrosion resistant, are excellent extricable in nature, exhibit moderate strength and finds many applications in the fields of construction (building and high way), automotive and marine engineering [6]. Ramesh et al. [7] concluded that Al6061–TiO_2 composite exhibited higher hardness, lower wear coefficient, when compared with the matrix alloy and Al6061–8 wt% TiO_2 possessed the lowest wear coefficient. Straffelini et al. [8] reported that the matrix hardness has a strong influence on the dry sliding wear behavior of Al6061–Al_2O_3 composites. Yu et al. [9] demonstrated the effects of applied load and temperature on the dry sliding wear behavior of Al6061–SiC composites and concluded that the wear rate decreases with increased applied load. How and Baker [10], in their investigation of wear behavior of Al6061-saffil fiber, concluded that saffil (Al_2O_3) is significant in improving wear resistance of the composites. Liang et al. [11] reported that the MMCs containing SiC particulates exhibit improved wear resistance. Basavarajappa et al. [12] stated that the microstructural characteristics, applied load, sliding speed and sliding distance affect the dry sliding wear and friction of MMCs and at higher normal loads (60 N), severe wear and silicon carbide particulate cracking and seizure of the composites occur during dry sliding. Basavarajappa and Chandramohan [13] reported that the sliding distance has the highest effect on the dry sliding wear behavior of MMCs than that of the load and sliding speed. Ramesh and Safiulla [14] studied wear behavior of hot extruded Al6061 based composites with SiC, Al_2O_3 and cerium oxide reinforcements, and concluded that wear rates of extruded Al6061–cerium oxide possessed the lowest wear rate under identical test conditions. Ramesh et al. [15] concluded that the increased content of silicon nitride particulates in Al6061 matrix alloy has resulted in higher hardness and ultimate tensile strength of the composites. The present studies are aimed at fabrication of Al6061–SiC composites containing various weight percentages of particulates and to study their density, microstructure, hardness, mechanical and wear resistance properties.

* Corresponding author. Tel.: +91 80 25183700x616; mobile: +91 9448323291, +91 9972455343; fax: +91 80 28440092.
E-mail address: veeru232@yahoo.com (G.B. Veeresh Kumar).

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Table 1
Chemical composition of Al6061 by weight percentage.

Chemical composition	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Al6061	0.62	0.23	0.22	0.03	0.84	0.22	0.10	0.1	Bal

2. Experimental details

The matrix material selected for the present studies was Al6061 alloy and was procured from Fenfee Metallurgicals, Bangalore, in the form of ingots. The chemical composition of Al6061 alloy is given in Table 1. The reinforcement material selected was Silicon Carbide (SiC) of size 150 μm supplied by M/s Snam Abrasives Pvt. Ltd., Hosur, Tamil Nadu. Table 2 is presented with the properties of matrix and reinforcing materials.

The fabrication of composites was carried out in liquid metallurgy route via stir casting technique. Preheated SiC powder of laboratory grade purity of particulate size 150 μm was introduced into the vortex of the molten alloy after effective degassing with solid degasser hexachloroethane tablet. Mechanical stirring of the molten alloy for a duration of 10 min was achieved by using ceramic-coated steel impeller. A speed of 400 rpm and a pouring temperature of 710 °C were maintained. The molten composite was poured into the preheated cast iron moulds. The extent of incorporation of SiC in the matrix alloy was varied from 2 to 6 wt% in the steps of 2. The cylinders of 22 mm × 210 mm cast composites of Al6061–SiC were obtained.

The cast composites were machined to prepare the test specimens according to ASTM standards. The density of material, which is ratio of weight to volume, was obtained by accurately measuring the weight and the volume of the composites. The prepared test specimens were subjected to metallographic, hardness, tensile and wear tests. Carefully polished and mirror finished specimens were examined under NIKHON – Japan make, ECLIPSE 150 model up right metallurgical microscope to obtain micrographs. MRB 250 model of Meta test make Brinell hardness tester served the purpose of measurement of hardness using a load of 500 kg for 30 s with a 10 mm steel ball. The mechanical properties were evaluated using Fine Spavy Associates model TUE – 400 °C of 400 kN capacity with least count of 4 N, fully computerized universal testing machine. Wear tests were conducted using a Ducom, Bangalore make computerized pin-on-disc machine. The test specimens were in the form of pins of diameter 10 mm and height 25 mm, while the disc was high carbon EN31 steel having a hardness of HRC 60. The wear height loss of the pin in microns was recorded during each wear test using an LVDT transducer of accuracy 1.0 μm. Due to wear of the pin surface during rubbing with counter disc, the pin continuously moves down to re-establish the contact with the disc surface. This linear downward movement of the pin is a measure of the wear height loss and is recorded by the LVDT. The surface roughness of the test pin specimen and the disc were maintained at 0.1 μm *R*a.

Table 2
Properties of Al6061 and SiC.

Properties	Al6061	SiC
Elastic modulus (GPa)	70–80	410
Density (g/cc)	2.7	3.1
Poisson's ratio	0.33	0.14
Hardness (HB500)	30	2800
Tensile strength (T)/compressive strength (C) (MPa)	115 (T)	3900 (C)

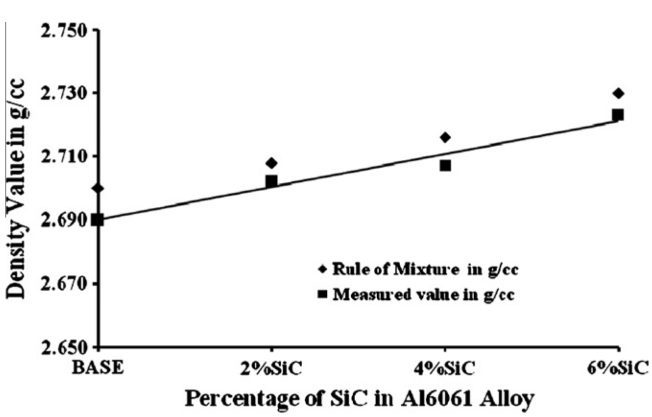

Fig. 1. Theoretical and experimental densities of Al6061–SiC composites.

3. Results and discussions

3.1. Density

This section presents the comparison of theoretical density obtained by rule of mixture and measured density values by experimentation for the composites studied. Fig. 1 shows the

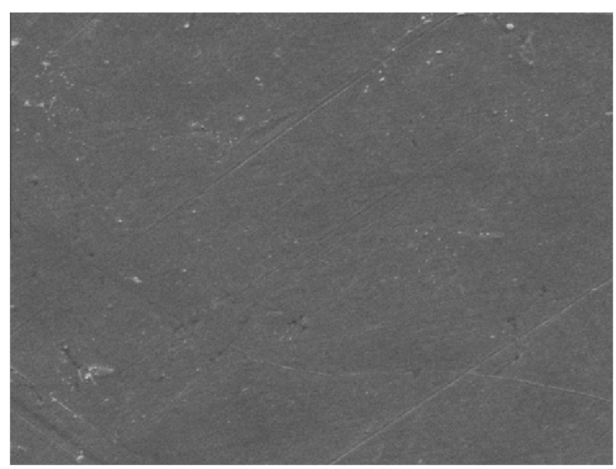

Fig. 2. Scanning electron micrograph of Al6061 alloy.

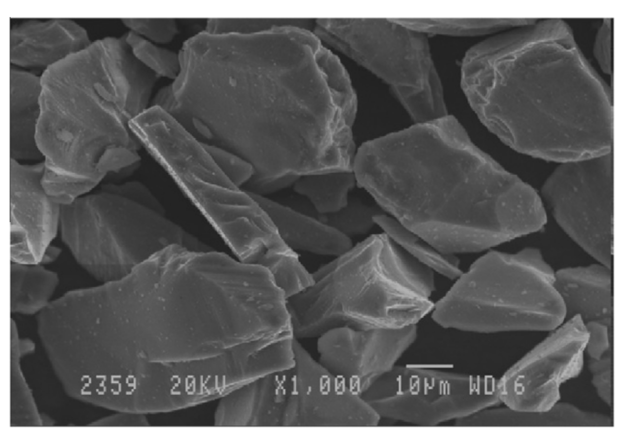

Fig. 3. scanning electron micrograph of silicon carbide powder.

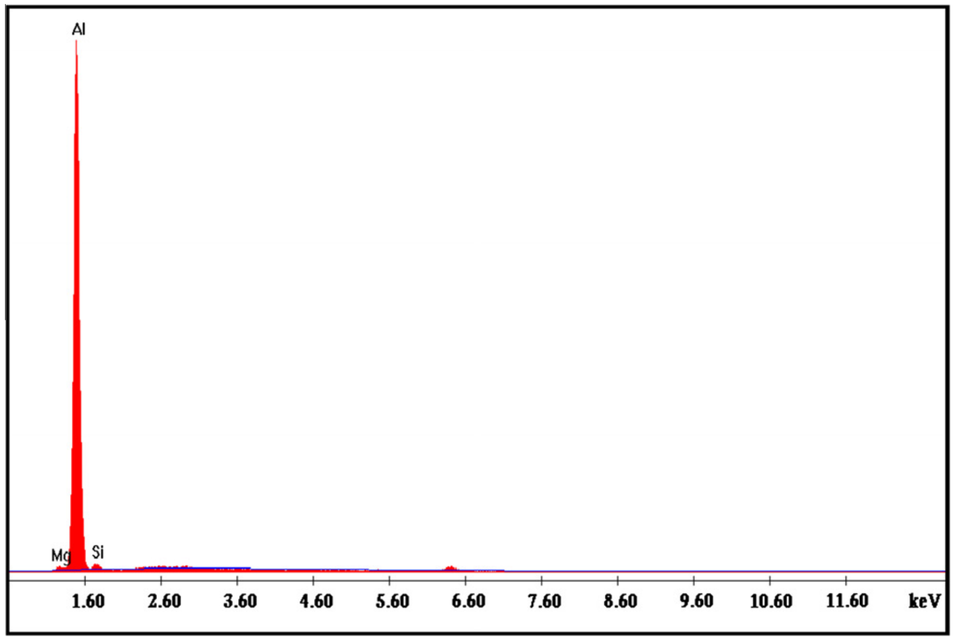

Fig. 4. Energy dispersive spectroscopy of Al6061-alloy.

experimental density values of the composites containing various filler percentages. From Fig. 1, it can be concluded that the experimental and the theoretical density values are in line with each other and confirm the suitability of the liquid metallurgy technique for the successful composite preparation. From Fig. 1 it can be observed that the density of composites are higher than that of the base matrix, further, the density increases with increased percentage of filler content in the composites. This increase in density of the Al6061–SiC composites is mainly attributed to the higher density of SiC than that of the Al6061. The density of the Al6061–SiC composite material increased by 1.30% as the SiC content increased from 0 to 6 wt%.

3.2. Microstructure studies

Fig. 2 shows the scanning electron micrograph of Al6061 alloy. The morphology of procured SiC powder is shown in Fig. 3, which show that the mixture of round and angular grains with sharp cornered morphology. Presence of magnesium and silicon particulates in aluminum is confirmed by carrying out EDAX analysis which is shown in Fig. 4.

Fig. 5a–d shows the optical micrographs of Al6061 alloy and Al6061–SiC composites. Micrographs reveal that there is fairly uniform distribution of SiC particulates throughout the matrix

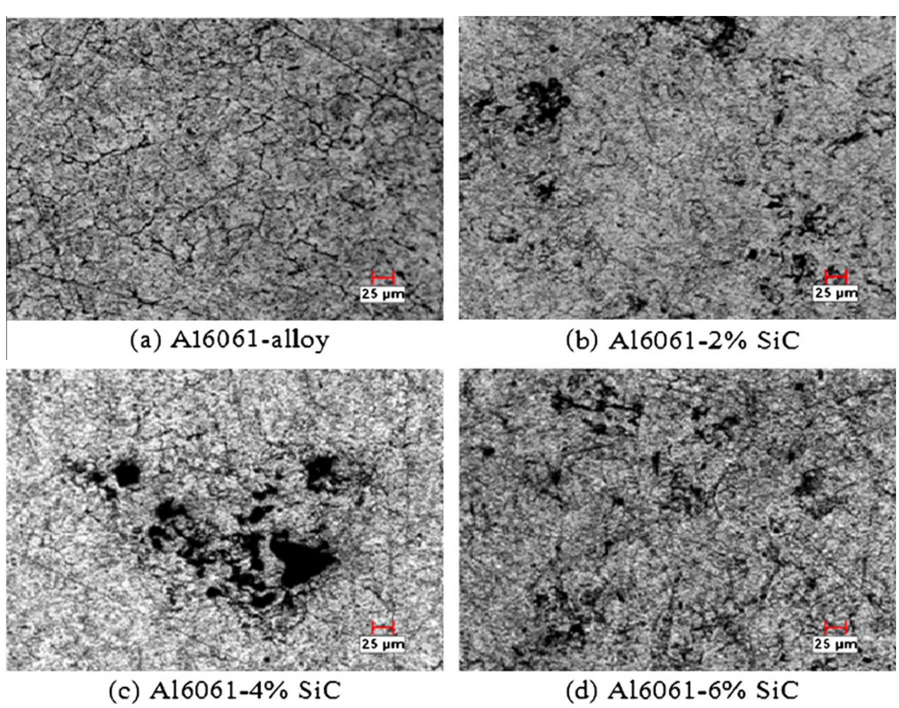

Fig. 5. (a)–(d) Optical micrographs of Al6061 alloy and its composites: (a) Al6061 alloy, (b) Al6061–2 wt% SiC, (c) Al6061–4 wt% SiC and (d) Al6061–6 wt% SiC.

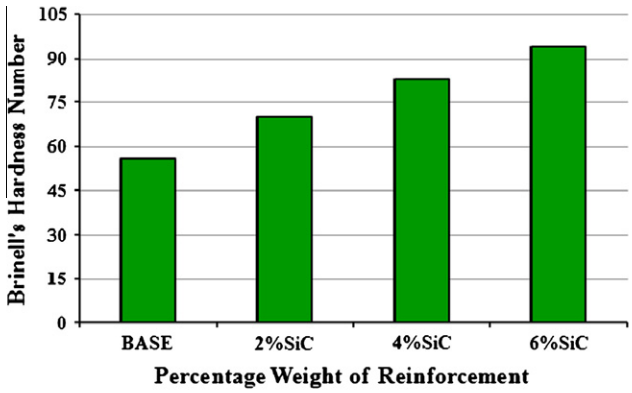

Fig. 6. Variation of Brinell hardness of Al6061–SiC composite with increased content of SiC.

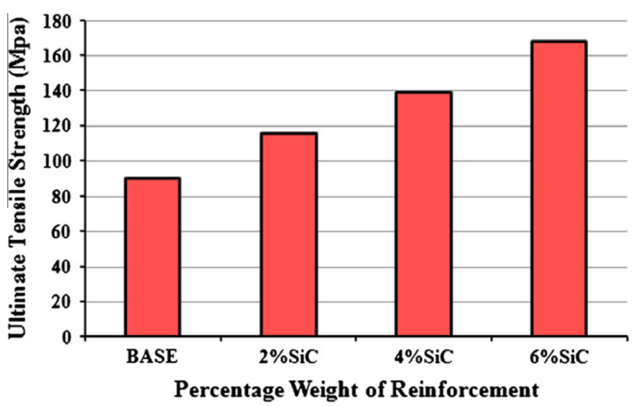

Fig. 7. Tensile strength of Al6061 alloy and its composites with increase in percentage reinforcement.

alloy. It is also being observed that porosity is lower. Further, from the optical micrographs, it can be seen that there is good bonding between the matrix and the reinforcement particulates resulting in better load transfer from the matrix to reinforcement material.

3.3. Hardness studies

The Brinell's hardness test was performed in accordance with ASTM E10-07a standard at room temperature condition (the diameter of the test was 20 mm and 15 mm in length). The Brinell's hardness of cast Al6061 matrix and its composites containing 2–6 wt% SiC is evaluated using a steel ball indenter at an applied load of 500 kg. Each value represented is an average of six measurements. The results are repeatable in the sense that each individual result did not vary more than 5% from the mean value. The hardness results are presented in Fig. 6. It can be observed that the hardness of the composite is greater than that of its cast matrix alloy. The composites containing higher filler content exhibits higher hardness. Hardness of the Al6061–SiC composite material increases by an amount of 67% as the content of SiC increases from 0 to 6 wt%. The improvement in the hardness can be attributed to the fact that the SiC possess higher hardness and its presence in the matrix improves the hardness of the composite.

Abdulhaqq et al. [16], concluded that incorporation of hard ceramic particulates resulted in significant increase in the bulk hardness of Al-matrix composites. Howell and Ball [17] reasoned the improvement of the hardness of composites to the increased particle volume fraction in the matrix material. Subramanian [18] incorporated silicon in Al-alloys and concluded that the higher wt% of Si improves the hardness of the composites. In general, the composites with the highest hardness and second-phase volume content are the most wear resistant, especially at higher load.

3.4. Ultimate tensile strength

The tensile test was performed in accordance with ASTM – E8/E8M-08 standard (the gauge diameter of the test specimen was 12 mm and 60 mm was the gauge length with 50 mm gripping surface length). The experiments were conducted at room temperature. Each result is an average of five readings. Fig. 7 shows variation of ultimate tensile strength with increase in percentage of SiC particulates. The ultimate tensile strength of the composite material increases by an amount of 86% as the content of silicon carbide particulates increase from 0 to 6 wt%. The structure and properties of the reinforcements control the mechanical properties of the composites that are reasoned to the strong interface that transfers and distributes the load from the matrix to the reinforcement exhibiting increased elastic modulus and strength [19].

In general, the particulate-reinforced Al-MMCs are recognized to have more improved elastic modulus, tensile and fatigue strength over monolithic alloys [9]. The strength of ceramic particulate reinforced Al-composites are found to increase by increased volume fraction of ceramic phase and by decreasing the size of the reinforcement in the composite, at the cost of reduced ductility [20].

3.5. Ductility

Fig. 8 presents the effect of SiC content on the ductility of cast Al6061–SiC particulate composites (measured in terms of percentage elongation). It can be seen from Fig. 8, that the ductility of the composites decreases monotonically and significantly with the increase in SiC content. The ductility drops by about 96% as the SiC content is increased from 0 to 6 wt%. This decrease in ductility in comparison with the matrix alloy is a most commonly encountered disadvantage in discontinuously reinforced MMCs. The reduction in ductility can be attributed to the presence of a hard ceramic phase that is prone to localized crack initiation and increased embrittlement effect due to local stress concentration sites at the reinforcement-matrix interface. Hence, the introduction of this hard secondary ceramic phase creates slip regions. Moreover, the reinforcing particulates resist the passage of dislocations either by creating stress fields in the matrix or by inducing large differences in the elastic behavior between the matrix and the dispersoid [21].

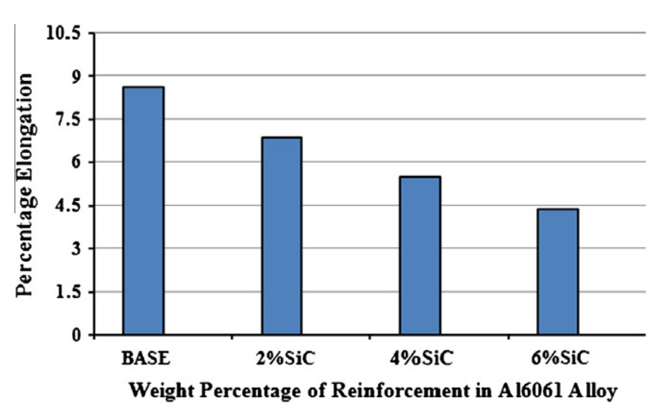

Fig. 8. Percentage elongation of Al6061 alloy and its composites with increase in percentage reinforcement.

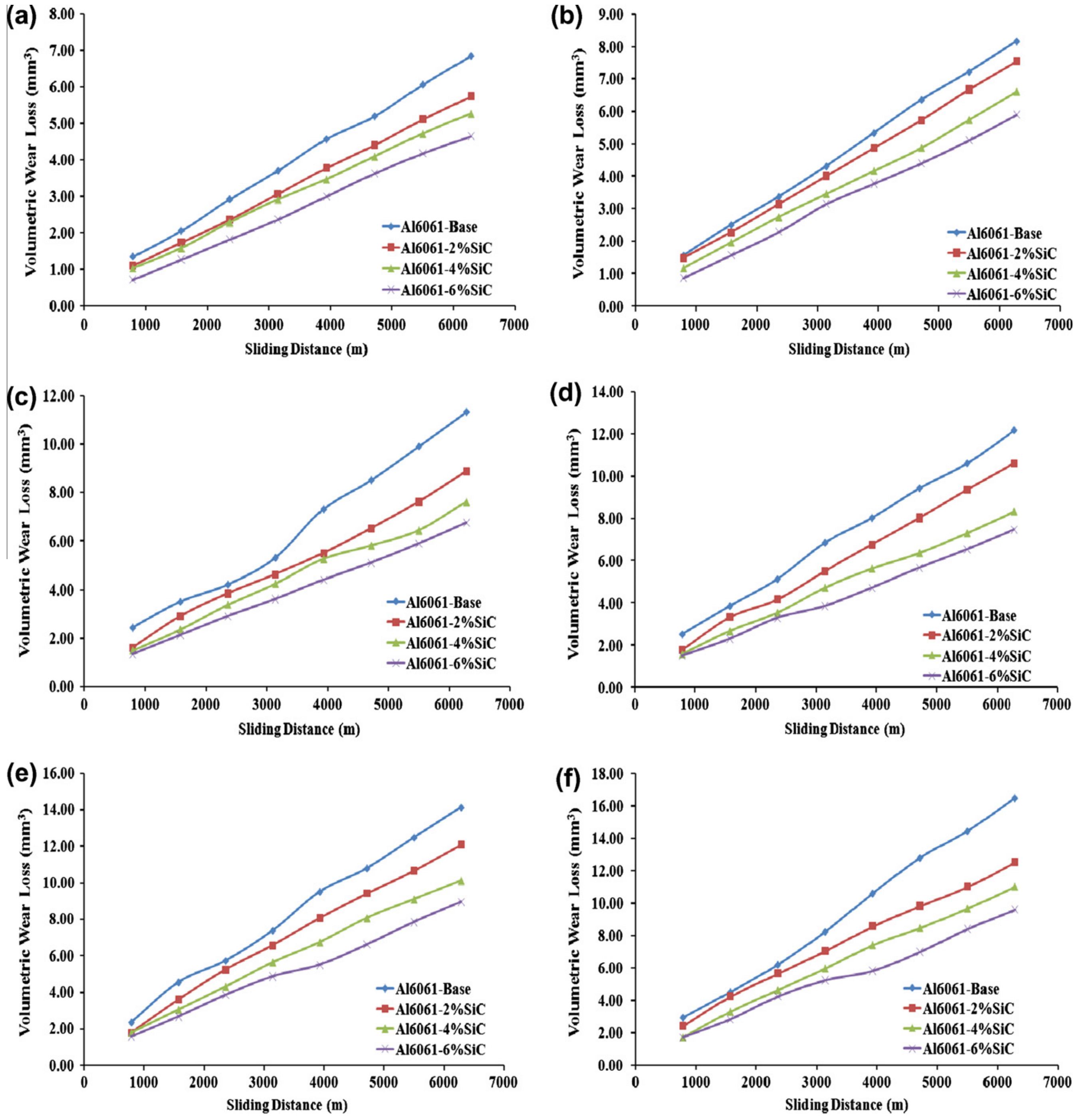

Fig. 9. Variation of volumetric wear loss of composites with sliding distance of 6 km, at an applied load of 10 to 60 N and sliding velocity 2.62 m/s. (a) Variation of volumetric wear loss of composites with sliding distance at a load of 10 N. (b) Variation of volumetric wear loss of composites with sliding distance at a load of 20 N. (c) Variation of volumetric wear loss of composites with sliding distance at a load of 30 N. (d) Variation of volumetric wear loss of composites with sliding distance at a load of 40 N. (e) Variation of volumetric wear loss of composites with sliding distance at a load of 50 N. (f) Variation of volumetric wear loss of composites with sliding distance at a load of 60 N.

3.6. Tribological studies

Dry-sliding wear experiments were conducted using a computer aided pin-on-disc wear-testing machine at constant sliding velocity ($V = 2.62\ ms^{-1}$) and load on the pin was varied from 10 to 60 N while the sliding distance of 6 km was maintained. The wear tests were conducted at room temperature in accordance with ASTM – G99 standard (diameter of the pin was 10 mm and 25 mm in length). During wear testing, height loss experienced by the pin specimen is measured in microns. Volume loss (mm^3) was calculated by multiplying the height loss with the area of cross-section of the pin.

The variation of volumetric wear loss with sliding distance is shown in Fig. 9a–f. With increase in sliding distance, there is higher volumetric wear loss for cast Al6061 and its SiC reinforced composites. At larger sliding distance, rise of temperature of the sliding surfaces are unavoidable. This results in softening of the matrix and composite pin surfaces leading to heavy deformation at higher sliding distances. This contributes to higher volumetric wear loss of matrix and the composite. As shown in Fig. 9, at all the sliding

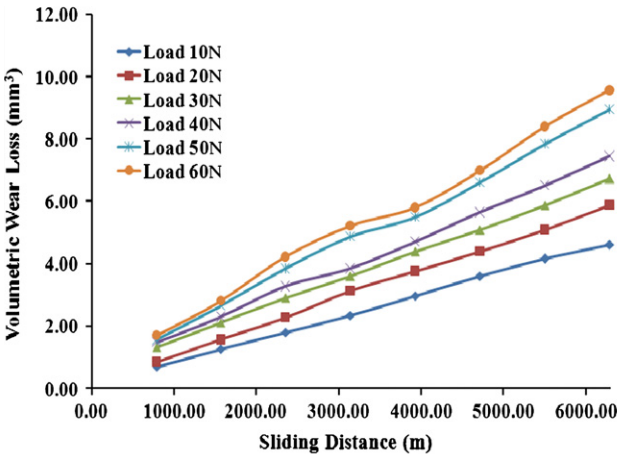

Fig. 10. Effect of applied load on the volumetric wear loss with increase in sliding distance on Al6061–6 wt% SiC composites.

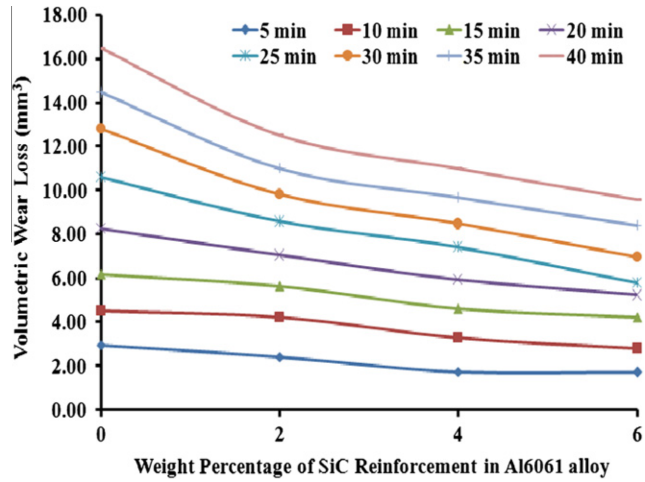

Fig. 11. Variation of volumetric wear loss with increase in percentage of reinforcement of cast Al6061 alloy and its SiC filled composites.

distances considered, the volumetric wear loss of the composites was much lower when compared with the matrix alloy and reduced with increased content of SiC in the composites. This can be attributed to enhancement in hardness of the composites. Increase in hardness results in improvement of wear and seizure resistance of materials. Particle reinforced composites possess better plastic forming capability than that of whisker or fiber reinforced composites. Moreover, these composites exhibit excellent heat and wear resistances due to the superior hardness and heat resistance characteristics of the particles that are dispersed in the matrix [22]. Among many ceramic materials, SiC and Al_2O_3 are widely in use, due to their favorable combination of density, hardness and cost effectiveness. When these reinforcements are combined with Aluminum, the resulting material exhibits significant increase in its elastic modulus, hardness, strength and wear resistance [23].

The variation of volumetric wear loss with load is shown in Fig. 10. Applied load affects the wear rate of Al-alloy and composites significantly and is the most dominating factor controlling the wear behavior [24]. The wear rate varies with the normal load, which is an indicative of Archard's law, and is significantly lower in case of composites [25]. With increase in loads, there is higher volumetric wear loss for matrix alloy and the composites. However, at all the loads considered, wear resistance of the composites were superior to the matrix alloy. Alpas and Zhang [26] indicated that under different applied load conditions identified three different wear regimes. At low load (regime I), the particles support the applied load in which the wear resistances of MMCs are in the order of magnitude better than Al-alloy. At regime II, wear rates of MMCs and Al-alloy were similar. At high load and the transition to severe wear (regime III), the surface temperatures exceed a critical value.

The variation of volumetric wear loss of matrix alloy and its composites with the increase in the SiC reinforcement content are shown in Fig. 11. It is observed that the volumetric wear loss of the composites decreases with increased contents of SiC

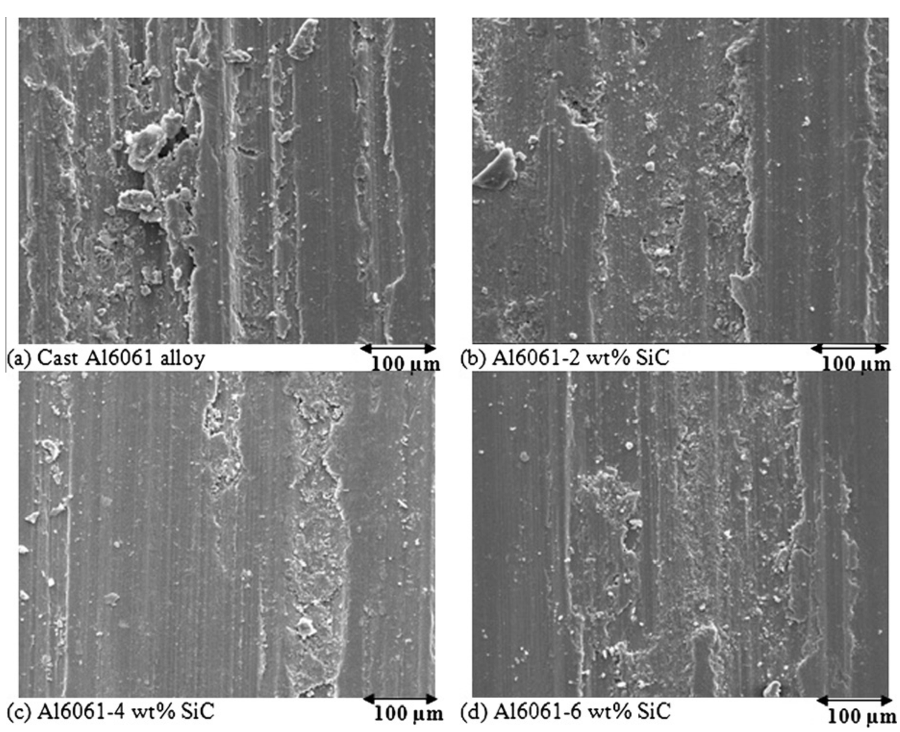

Fig. 12. SEM photographs of worn surfaces of cast Al6061 alloy and its SiC filled composites at an applied load of 60 N and sliding distance of 6 km.

reinforcement in the matrix alloy. However, for a given reinforcement content, the composites possess lower volumetric wear loss than the cast Al6061 alloy. The improvement in the wear resistance of the composites with increased contents of SiC reinforcement can be attributed to the improvement in the hardness of the composites and improved hardness results in decrease in volumetric wear loss. The wear resistance of MMCs can be improved by increasing the volume fraction of the reinforcing ceramic phase by as much as 70% [27]. Also the dry sliding wear resistance increases with increase in particle volume fraction. At higher volume fraction, the friction coefficient was found higher and there was almost no effect of load on friction coefficient [28].

Fig. 12 shows the SEM photographs of worn surfaces of cast Al6061 alloy and its SiC filled composites at an applied load of 60 N and sliding distance of 6 km. The presence of wear debris particles is a clear indication of the adhesive and abrasive wear, with plastic shearing of the asperities, had occurred during the wear test. The SEM micrographs also show some damaged regions, which may form flake shaped debris. In Al-based MMCs with reinforcing phases, such as SiC and Al_2O_3, is the tendency of the reinforcement to act as a second-body abrasive against the counterface, increasing counterface wear. In addition, reinforcement liberated as wear debris acts as a third-body abrasive to both the matrix and reinforcement surfaces. At 60 N load, the composites of 6 wt% SiC exhibits lower wear loss. At higher load, degree of grooves formed at the worn surface of the matrix alloy and composites containing lower volume fractions of SiC reinforcement are quite larger and undergo severe plastic deformation leading to severe wear. This phenomenon is quite evident from SEM photographs shown in Fig. 12a–d. The amount of grooving in the worn surfaces of the composites is reduced with increased content of SiC indicating lower material removal in comparison with matrix material without reinforcement as evidenced in SEM photograph shown in Fig. 12a.

4. Conclusions

The significant conclusions of the studies carried out on Al6061–SiC MMCs are as follows.

The Liquid metallurgy technique (stir casting route) was successfully adopted in the preparation of Al6061–SiC composites containing the filler contents up to 6 wt%. The density of the composites was found to have improved than the matrix. The microstructural studies revealed the uniform distribution of the particulates in the matrix system. Hardness of the composites was found to increase with increased filler content. The ultimate tensile strength properties of the composites are found to be higher than that of base matrix and Al6061–6 wt% SiC composite tensile strength property is superior than other composites studied. The wear resistance of the composites is higher than that of base alloy. Increased applied load and sliding distances resulted in higher volumetric wear loss. Further, the SiC reinforcement contributed significantly in improving the wear resistance of Al6061–SiC composites. Overall, it can be concluded that Al6061–6 wt% SiC exhibits superior mechanical and tribological properties compared with Al6061, Al6061–2 wt% SiC and Al6061–4 wt% SiC composites.

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