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JOURNAL OF COMPOSITE MATERIALS

Journal of Composite Materials
46(10) 1201–1209

DOI: 10.1177/0021998311414948
jcm.sagepub.com
SAGE

Mechanical and dry sliding wear behavior of Al7075 alloy-reinforced with SiC particles

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Abstract

In this article, the experimental results of the mechanical and tribological properties of Al7075–SiC composites are presented. The composites of Al7075 containing 2–6 wt% SiC were fabricated by liquid metallurgy route. The experimental results showed that the density of the composites increase with increased SiC contents and are in line with the values obtained by the rule of mixtures. The hardness and tensile strength of the Al7075–SiC composites are found to be increased by increased volume percentage of ceramic phase at the cost of reduced ductility. The wear properties of the composites containing SiC exhibited the superior wear-resistance properties.

Keywords

Metal–matrix composites, Al7075, SiC, mechanical properties, dry sliding wear

Introduction

Aluminum alloys are preferred engineering materials in automobile, aerospace, and mineral-processing industries for making various highly performing components that are being used for various applications owing to their lower weight and excellent thermal conductivity properties. Among several series of aluminum alloys, Al7075 is much explored. Al7075 alloy possesses very high strength, higher toughness, and are preferred in aerospace and automobile sectors.[1] However, aluminum alloys exhibit poor tribological properties. Consequently, the study of the tribological behavior of aluminum-based materials is becoming increasingly significant. Al–Si alloys, for example, have been extensively studied in this regard.[2] The composites formed out of aluminum alloys are of wide interest owing to their high strength, fracture toughness, wear resistance, and stiffness. Also, these composites are of superior in nature for elevated temperature applications when reinforced with ceramic particles.[3] The ceramic particulate-reinforced composites find applications as cylinder blocks, pistons, piston insert rings, brake discs, and calipers.[4] It has been reported that the wear resistance of composite increases with increase in volume fraction of the reinforcements.

Reda et al.[5] and Clark et al.[6] in their studies, reported that pre-aging of Al7075 at various retrogression temperatures improves the hardness, tensile properties, and electrical resistivity. Kim et al.[7] concluded that the hardness of aged Al7075 alloy increases and they reported that the squeeze casting method improves the grain refinement, thereby reducing the wear loss when compared to that of manufacture adopting non-pressurized casting methods. Bystritskii et al.[8] in an attempt of surface modification of Al7075 alloy using microsecond plasma-opening switch technology, reported the enhanced fatigue lifetime of these alloys. Further, these alloys are of much interest when they are reinforced with hard-phase particle[9] and whisker reinforcements. From the literatures, the most preferred particle reinforcements for the production of metal–matrix composites (MMCs) are the hard ceramics, namely, zirconia, alumina, and silicon carbide (SiC) that enhance the properties like strength, stiffness, wear, corrosion resistance, fatigue life, and also elevated temperature properties. Kumar and

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Balasubramanian[10] while developing a mathematical model for dry sliding wear behavior of Al7075–SiC composites reported that increased SiC in base alloy reduces the wear rate of the composites by restricting the flow or deformation of the matrix material against applied load. Dasgupta and Meenai[11] stated that the improvement in the hardness, mechanical properties, and wear resistance are attained by heat treatment of composites. Doel and Bowen[12] in their study concluded that the 5- and 13-μm particle sized SiC-reinforced Al7075 exhibit improved tensile strength and lower ductility. Komai et al.[13] reported the superior mechanical properties of Al7075–SiC composites. Ma et al.[14] observed higher wear rate with composites containing SiC_w than with those containing SiC_p.

The SiC reinforcement in the Al–matrix composites is the most fracture resistant when compared with $A1_2O_3$ and Si.[15]

Zhang and Wang[16] during their investigation of the friction and wear behavior of Al–MMCs reinforced with different sizes of SiC particulates to 25 vol.% found that parts of the removed SiCp are entrapped between two partners leading to three-body abrasion. Further, the friction performances and wear resistance observed for the brake material against the drum with large-size SiCp were better than those against the drum with small-size SiCp. Rao and Das[17] investigated the effect of sliding distance on the wear and friction behavior of as-cast and heat-treated Al–SiCp composites and found that the heat-treated composite exhibited superior wear properties than the base alloy. It was observed that prolonged duration of layer transfer resulted in adhesion kind of wear. During the investigation, the sliding friction and wear behavior of aluminum (Al), aluminum alloy 7075 (Al7075), and SiC particulate-reinforced aluminum matrix composites (Al–SiC) under dry sliding wear conditions, Venkataraman and Sundararajan[18] found that a hard brittle oxide layer called mechanical mixed layer (MML) formed on the surface of the specimen which was responsible for the decrease in the wear rate and friction of the MMCs. The MML formed on the worn surface of matrix and composite served as a protective layer and a solid lubricant. Formation of the tribo-layer delayed the mild-to-severe wear transition in Al–MMCs. Removal of this MML was responsible for the severe wear of the Al7075–SiC composites under dry sliding wear conditions.

From the above discussion, it can be concluded that there are no enough data available on the mechanical, and wear resistance properties of particulate-reinforced Al7075 composites. Hence, this study is aimed at the fabrication of Al7075–SiC composites containing various weight percentages of particles and to study their density, microstructure, hardness, mechanical, and wear resistance properties.

Experimental details

The base matrix selected for this study was Al7075 alloy and procured from Fenfee Metallurgicals, Bangalore, in the form of ingots. The chemical composition of Al7075 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 morphology of procured SiC powder is shown in Figure 1.

The preparation of composites has been done through liquid metallurgy route *via* stir casting technique. Preheated SiC powder of laboratory-grade purity of particle 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 using ceramic-coated steel impeller. A speed of 400 rpm was maintained. A pouring temperature of 710°C was maintained and the molten composite poured into the preheated cast iron molds. The

Table 1. Chemical composition of Al7075 by weight percentage

Chemical composition	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Al7075	0.4	0.5	1.6	0.3	2.5	0.15	5.5	0.2	Bal

Table 2. Properties of Al7075 and SiC

Properties	Al7075	SiC
Elastic modulus (GPa)	70–80	410
Density (g/cc)	2.81	3.1
Poisson's ratio	0.33	0.14
Hardness (HB500)	60	2800
Tensile strength (*T*)/compressive strength (*C*) (MPa)	220 (*T*)	3900 (*C*)

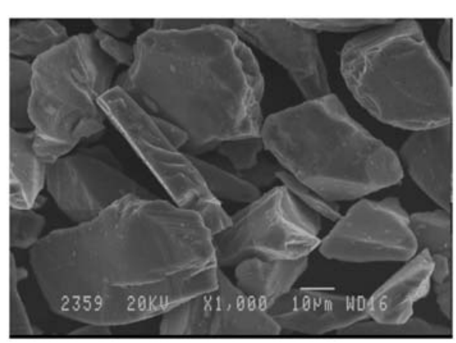

Figure 1. Scanning electron micrograph of silicon carbide powder.

extent of incorporation of SiC in the matrix alloy was varied from 2 to 6 wt% in steps of 2. The cylinders of $22 \times 210\,mm^2$ cast composites of Al7075–SiC were obtained.

The cast composites were machined to prepare the test specimens according to ASTM standards. The density of material, which is the 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 upright metallurgical microscope to obtain microphotographs. 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 Magnum 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 a linear variable differential transducer (LVDT) of least count 1.0 µm. On wearing 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 measurement of the wear height loss and is recorded by the LVDT. The surface roughness values of the test pin specimen and the disc were maintained at 0.1 µm R_a.

Results and discussion

Density

This section is presented with the comparison of theoretical density obtained by rule of mixtures and measured density values by experimentation for the composites studied. Figure 2 shows the experimental density values of the composites containing various filler percentages. From Figure 2, it can be concluded that the experimental and the theoretical density values are in line with each other and confirms the suitability of the liquid metallurgy techniques for the successful composite preparation. From Figure 2, it can be observed that the densities of composites are higher than those of the base matrix; further, the density increases with increased percentage of filler content in the composites.[19] This increase in density of the Al7075–SiC composites is mainly attributed to the fact that the reinforcemnt material SiC possesses higher density than that of the Al7075 alloy. The density of the Al7075–SiC composite material increased by an amount of 1.24% as the SiC content increased from 0 to 6 wt%.

Microstructure studies

Figure 3(a)–(d) shows the optical microphotographs of Al7075 alloy and Al7075–SiC composites at 200× magnification. Microphotographs reveal that there is fairly uniform distribution of SiC particles throughout the matrix alloy. It is also evident from the optical microphotographs that lesser extent of porosity is observed. Also, from the optical microphotographs, it can be seen that there is a good bonding between the matrix and the reinforcement particles; hence, better load transfer

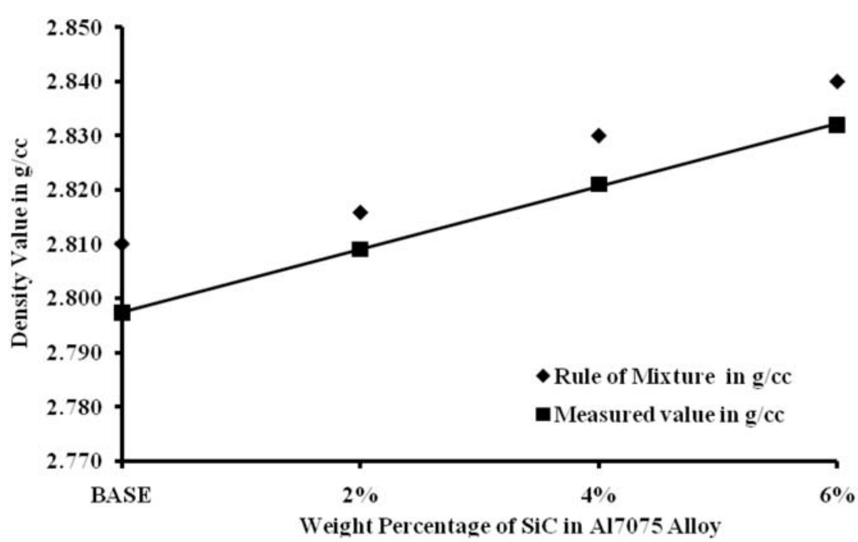

Figure 2. Theoretical and experimental densities of Al7075–SiC composites.

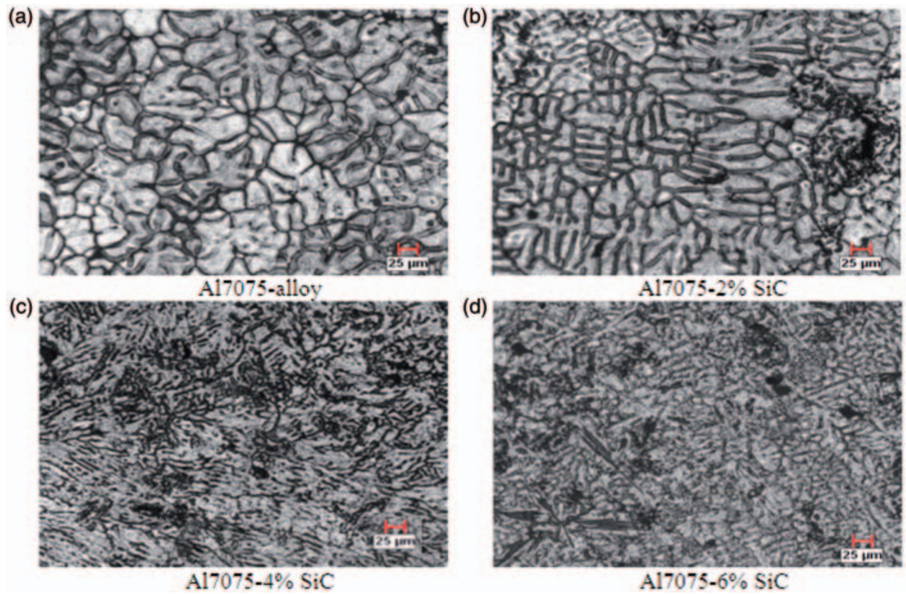

Figure 3. Optical microphotographs of Al7075 alloy and its composites: (a) Al7075 alloy, (b) Al7075–2 wt% SiC, (c) Al7075–4 wt% SiC, and (d) Al7075–6 wt% SiC.

from the matrix to reinforcement material. It is reported that higher hardness is always associated with lower porosity of MMCs.[20]

Hardness studies

The hardness is one of the most important property of materials through which the strength, wear resistance, and interface bonding strength between the matrix and reinforcement can be estimated. The Brinell's hardness test was performed in accordance with ASTM E10-07a standard at room temperature condition (the diameter and length of the test specimen were 20 mm and 15 mm, respectively). The Brinell's hardness of cast Al7075 base matrix and its composites containing 2–6 wt% SiC are evaluated using a steel ball indenter at an applied load of 500 kg and is shown in Figure 4. From Figure 4, it can be observed that the hardness of the composite is superior to that of its cast matrix alloy. The composites containing higher filler content exhibits superior hardness. Hardness of the Al7075–SiC composite material increases by an amount of 62% 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 possesses higher hardness and its presence in the base matrix improves the hardness of the composite.[21]

Hamid et al.[22] declared the significant increase in the bulk hardness of Al–matrix composites incorporated with hard ceramic particles. Howell and Ball[23] reasoned the improvement of the hardness of composites to the increased particle volume fraction. Subramanian[24] 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 high loads. Several investigators have also projected that wear resistance of a material depends on its hardness.[25]

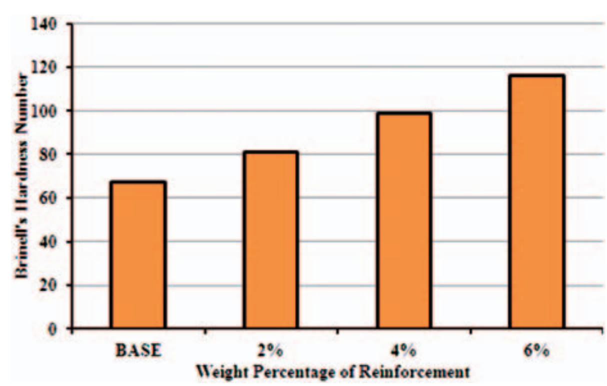

Figure 4. Variation of Brinell hardness of Al7075–SiC composite with increased content of SiC.

Ultimate tensile strength

The tensile test was performed in accordance with ASTM – E8/E8M-08 standard (the gage diameter and gage length of the test specimen were 12 mm and 60 mm, respectively, with 50 mm gripping surface). The experiments were conducted at room temperature. The mechanical properties of the composites are of immense importance for different applications. Figure 5 shows the

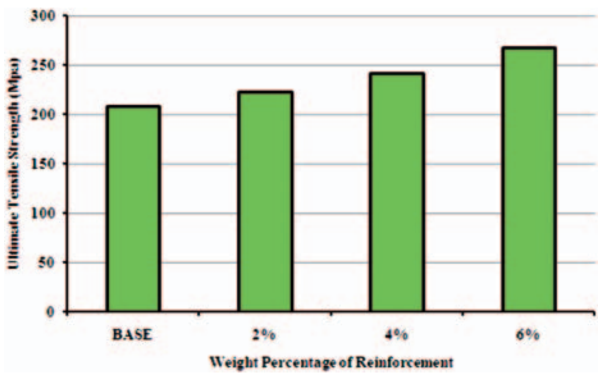

Figure 5. Ultimate tensile strength of Al7075 alloy and its composites with increase in SiC percentage reinforcement.

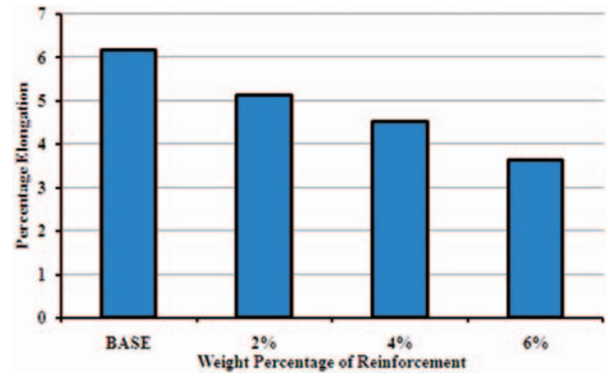

Figure 6. Percentage elongation of Al7075 alloy and its SiC-filled composites.

variation of ultimate tensile strength with increase in percentage of SiC particles. The ultimate tensile strength of the composite material increases by an amount of 29% as the content of SiC particles increases 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 distributes and transfers the load from the matrix to the reinforcement exhibiting increased elastic modulus and strength.[26]

In general, the particle-reinforced Al–MMCs are recognized to have more enhanced elastic modulus, tensile, and fatigue strengths over monolithic alloys.[27] The strength of ceramic particle-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.[15]

Ductility

Figure 6 presents the effect of SiC content on the ductility of cast Al7075–SiC particulate composites (measured in terms of percentage elongation). It can be seen from the Figure 6 that the ductility of the composites decreases monotonically and significantly with the increase in SiC content. The ductility drops by about 70% as the SiC content is increased from 0 to 6 wt%. These results tally with those obtained by other researchers[28] who also observed that the ductility of the composites decreases with increase in the reinforcement content. This decrease in ductility in comparison with the matrix alloy is the most commonly encountered disadvantage in discontinuously reinforced MMCs.[29]

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.[30]

Tribological studies

Dry sliding wear experiments were conducted using a computer-aided pin-on-disc wear-testing machine at constant sliding velocity ($V = 2.62$ m/s) and load on the pin 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 and the length of the pin were 10 and 25 mm, respectively). 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 Figure 7(a)–(f). With increase in sliding distances, there is higher volumetric wear loss for the matrix and the composites. At larger sliding distances, higher increases 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 Figure 7, at all sliding 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.[31]

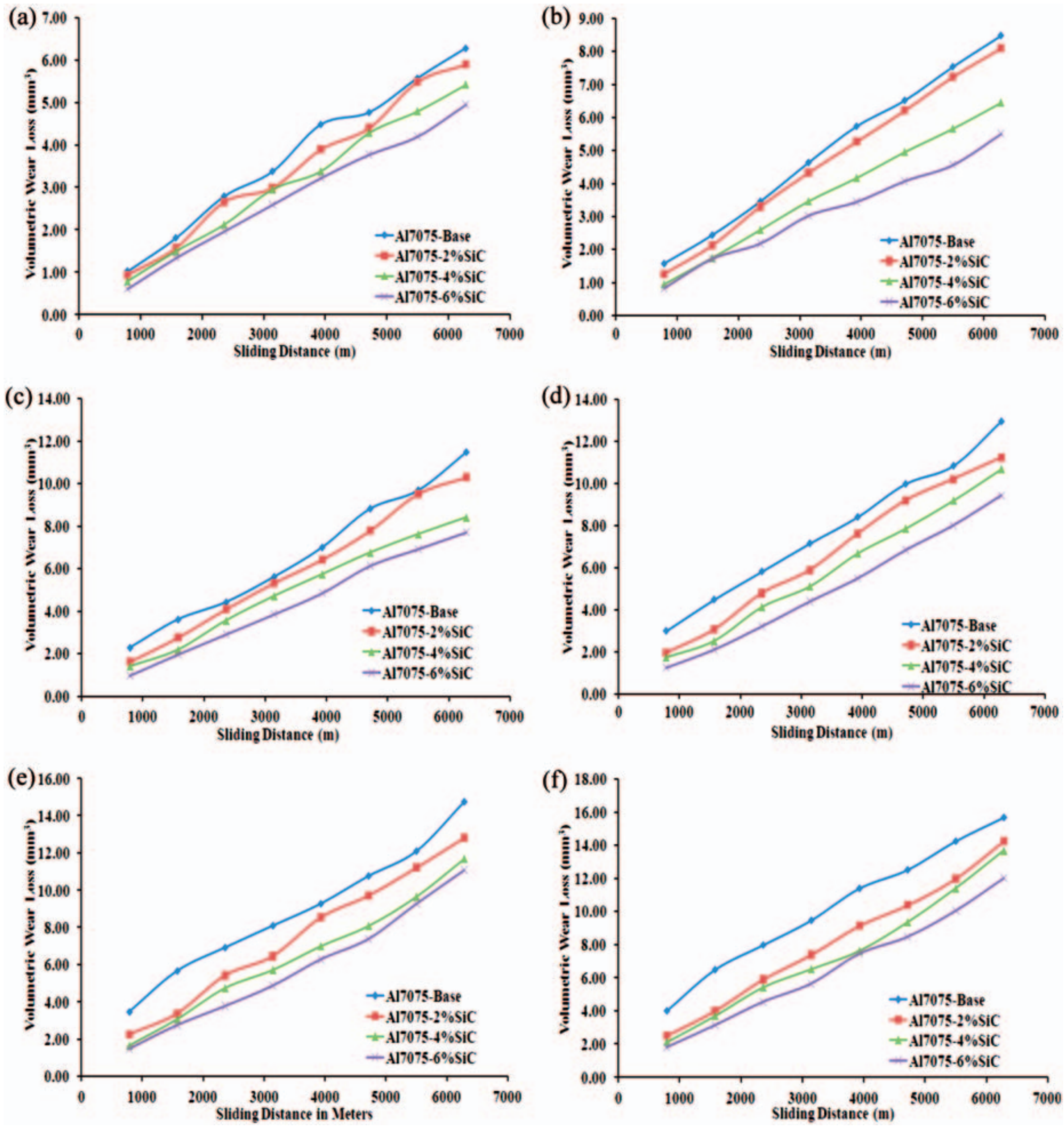

Figure 7. Variation of volumetric wear loss of composites with sliding distance of 6 km, sliding velocity 2.62 m/s, and loads of: (a) 10 N, (b) 20 N, (c) 30 N, (d) 40 N, (e) 50 N, and (f) 60 N.

The variation of volumetric wear loss with load is shown in Figure 8. Applied load affects the wear rate of Al alloy and composites significantly and is the most dominating factor controlling the wear behavior.[32] The wear rate varies linearly[22] with the normal load, which is an indicative of Archard's law, and is significantly lower in case of composites.[33] 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 was superior to the matrix alloy. Increased loads will result in onset of delamination, leading to higher volumetric wear loss of the matrix and its composites as observed by several researchers.

The variation of volumetric wear loss of matrix alloy and its composites with the increase in the SiC reinforcement content is shown in Figure 9. It is observed that the volumetric wear loss of the composites decreases with increased contents of SiC reinforcement in the matrix alloy. However, for a given reinforcement content, the composites possess lower volumetric wear loss than the cast Al7075 alloy. The improvement in the

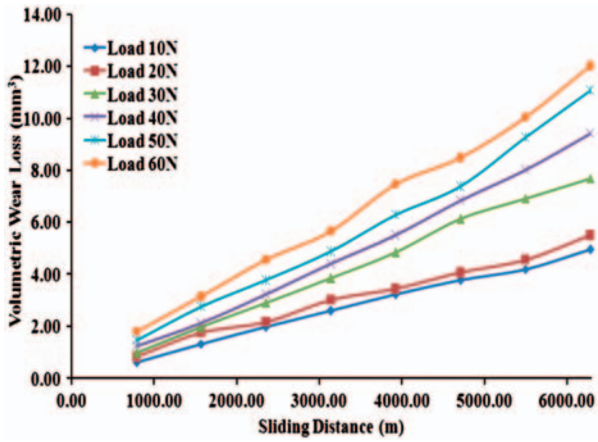

Figure 8. Effect of applied load on the volumetric wear loss with increase in sliding distance in Al7075–6 wt% SiC composites.

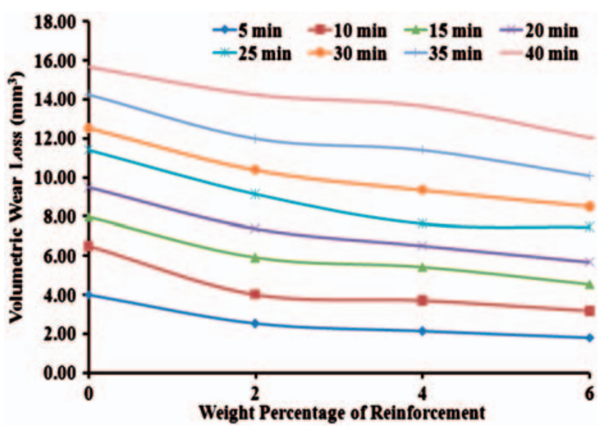

Figure 9. Variation of volumetric wear loss with increase in percentage of reinforcement of cast Al7075 alloy and its SiC-filled composites.

wear resistance of the composites with increased contents of SiC reinforcement can be attributed to the improvement in the hardness of the composites. Improved hardness results in decrease in wear rate as reported by numerous researchers.[31]

Figure 10 presents SEM photographs of worn surfaces of cast Al7075 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, 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, there is a 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.[34] At 60 N load, the composites of 6 wt% SiC exhibit 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. The SEM shows the presence of heavy wear debris particles on their worn surfaces. This phenomenon is quite evident from SEM photographs, as shown in Figure 10(a)–(d). The amount of grooving in the worn surfaces of the composites, as shown in Figure 10(b)–(d), is reduced with increased content of SiC, indicating lower material removal in comparison with matrix material without reinforcement, as shown in Figure 10(a).

Conclusions

The significant conclusions of the studies carried out on Al7075–SiC MMCs are as follows.

- The liquid metallurgy techniques (stir casting route) were successfully adopted in the preparation of Al7075–SiC composites containing the filler contents upto 6 wt%.
- The densities of the composites are found to be improved than their base matrix. The density of the Al7075–SiC composite material increased by an amount of 1.24% as the SiC content increased from 0 to 6 wt%.
- The microstructural studies revealed the uniform distribution of the particles in the matrix system. There is a good bonding between the matrix and the reinforcement particles; hence, better load transfer from the matrix to reinforcement material.
- The hardness of the composites found to be increased with increased SiC filler content. Hardness of the Al7075–SiC composite material increases by an amount of 62% as the content of SiC increases from 0 to 6 wt%.
- The ultimate tensile strength properties of the composites are found to be higher than those of base matrix, and Al7075–6 wt% SiC composites superior tensile strength properties than other composites studied. The ultimate tensile strength of the composite material increases by an amount of 29% as the content of SiC particles increases from 0 to 6 wt%, at the cost of reduced ductility. The ductility drops by about 70% as the SiC content is increased from 0 to 6 wt%.
- The wear resistance of the composites is higher than that of base matrix alloy. Increased applied loads and sliding distances resulted in higher volumetric wear loss.
- The SiC reinforcement contributed significantly in improving the wear resistance of Al7075–SiC

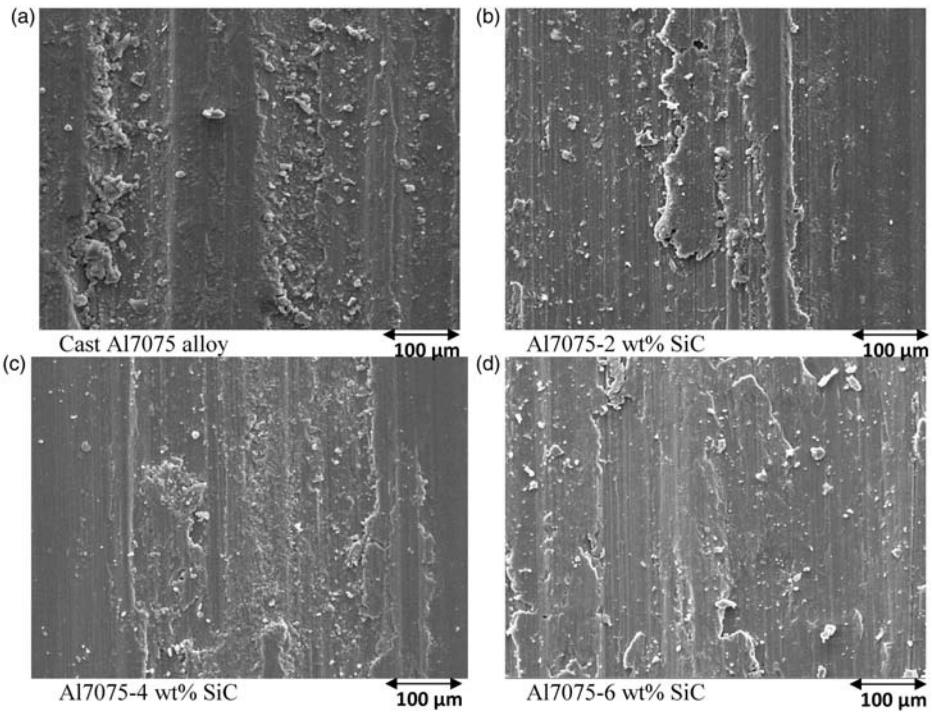

Figure 10. SEM photographs of worn surfaces of cast Al7075 alloy and its SiC-filled composites at an applied load of 60 N and sliding distance of 6 km.

composites. From the overall studies, it can be concluded that Al7075–6 wt% SiC exhibits superior mechanical and tribological properties.

- The SEM photographs of worn surfaces of cast Al7075 alloy and its SiC-filled composites clearly indicated that the amount of grooving in the worn surfaces of the composites is reduced with increased content of SiC, indicating lower material removal.

Acknowledgments

The authors thank the management of Amrita School of Engineering, Amrita Vishwa Vidyapeetham University, Bangalore, for their support and encouragement during the research studies.

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