Effect of B₄C and SiC nanoparticle reinforcement on the wear behavior and surface structure of aluminum (Al6063-T6) matrix composite

N. Ramadoss¹ · K. Pazhanivel² · S. Ganesh Kumar³ · M. Arivanandhan⁴ · P. Anandan⁵

Received: 19 December 2019 / Accepted: 7 April 2020 / Published online: 15 April 2020
© Springer Nature Switzerland AG 2020

Abstract

In this study, boron carbide (B₄C) and silicon carbide (SiC) nanoparticle reinforced aluminum matrix composites (AMC) were fabricated by stir cast method. The morphology of the SiC and B₄C nanoparticles are analysed by scanning electron microscope (SEM). The Electron probe microanalysis and energy dispersive spectroscopic analysis were employed to confirm the dispersion of nano SiC and B₄C particles in the aluminum matrix. The abrasion wear behavior of these composite materials was investigated under normal loads of 10 N, 20 N and 30 N. The effect of reinforcing materials on wear behaviour was investigated and the reinforced composites exhibits relatively high wear resistance compared to pure Al6063-T6 alloy. Wear resistance of the B₄C reinforced AMCs was relatively higher than that of SiC reinforced AMCs at all the applied loads. SEM images of the worn surfaces revealed that micro fracture of the reinforcement composites was the predominant mechanism associated with 3 body abrasion wear. Moreover, SEM images revealed that the debris and detached particle formations are more in the nanoparticle reinforced AMCs. A strong interfacial interactions between Al matrix and SiC nanograin with strong Al–Si bonding is responsible for the high wear resistance. The wear mechanism is varied from abrasive to oxidative by increasing the normal load in all the samples. Moreover, the formation of a condensed spinel structure with the consistent matrix/particle interface bonding provides a substantial particle strengthening effect.

Keywords Antiwear additives · Friction · Abrasive wear · Wear mechanism · EDS · SEM

1 Introduction

Aluminum(Al) alloys are promising structural materials. However, it is necessary to improve the wear resistance for various applications. In particular, uses of aluminum alloys in automotive applications have been limited due to their inferior strength, rigidity and low wear resistance, as compared to those of ferrous alloys. Particle reinforced aluminum composites, offer reduced mass, high stiffness, specific strength and improved corrosion resistance, facilitating the possibility of replacing iron-base materials by particle reinforced Aluminum Metal Matrix Composites

(AMMCs) in automotive applications [1]. Significant improvement have been observed in the SiC reinforced aluminum matrix and B₄C reinforced aluminum matrix composite systems [2, 3]. Ceramic materials have excellent mechanical properties of hardness, thermal strength and chemical stability. Hence, it is expected that the use of ceramics and associated composites will find different industrial applications [3, 4]. However, they are not yet used widely as tribal-material in industrial fields owing to the constraints in their fabrication process and for the fact that friction and wear properties of ceramics depend on sliding environment.

✉ P. Anandan, anandantcet@gmail.com | ¹Department of Mechanical Engineering, ARM College of Engineering and Technology, Maraimalai Nagar, Chennai 603 209, India. ²Department of Mechanical Engineering, ARS College of Engineering, Maraimalai Nagar, Chennai 603 209, India. ³Department of Mechanical Engineering, Thiruvalluvar College of Engineering and Technology, Vandavasi 604505, India. ⁴Centre for Nanoscience and Technology, Anna University, Chennai 600025, India. ⁵Department of Physics, Thiru Kolanjiappar Government Arts College, Vriddhachalam 606001, India.

Metal matrix composites (MMC) are prepared using different techniques, which could be classified as liquid phase (casting) processes [5], vacuum infiltration [6], pressure less infiltration [7] solid state processing and ultrasonic dispersion methods [8]. Solid state processing involves powder metallurgy (PM) route while liquid phase processing involves casting and semisolid forming [2]. Ultrasonic based stirring techniques in liquid casting are extensively used for the preparation of particulate composite, in the process the matrix is in molten state, reinforcing materials are in the form of powder [9] and aluminum is the commonly used matrix for MMC. However, much of the attention is on the dry sliding and erosion wear behavior of MMCs with various reinforcements such as B_4C , SiC, Al_2O_3 , TiC, TiB_2 , MgO, TiO_2 , AlN, BN and Si_3N_4 and nano particles [3, 10, 11]. Many methods were developed to prepare the composites by addition of various particles into pure Aluminum [12, 13], which include powder metallurgy, stir casting and squeeze casting.

Literature review reveals that many studies have been carried out on mechanical behavior of SiC and B_4C reinforced Al composites developed by stir casting techniques. B_4C is effective in suppressing the transition to a severe wear rate, increasing hardness and tensile strength [14–17]. The wear resistance of SiC particulate reinforced composites are superior to that of Al [18]. SiC particles reinforcement improved the abrasion resistance against all the abrasives used. This improvement generally was higher against alumina [19]. The wear increased with increasing applied normal load, abrasive size and sliding distance for SiC particles [20]. Mechanical properties of the as-cast MMCs have been improved significantly even with a low weight fraction of nano-sized SiC [21]. The wear loss of composites as well as the matrix alloy increased with the increase in applied load and sliding distance. Optical and Scanning Electron micrographs of the wear surface and subsurface of the composite specimens revealed the wear mechanism of the composite. The interface bond between silicon particle and Aluminum matrix is the main reason for change of wear property of composites under different applied loads [22–24]. The mechanical properties like hardness and tensile strength have improved with the increase in weight percentage of B_4C particulates in the aluminum matrix [25].

The exhaustive literature survey reveals that extensive work has been reported to improve properties of Aluminium Metal Matrix Composites reinforced with Silicon carbide particle in both untreated and precipitation hardening condition [26]. Brake pads are developed with light aluminum alloy reinforced with SiC to augment the strength and wear resistance and explore the advantage of low density of the matrix [27]. The work-hardening effects of the added nanoparticles, and its intrinsic hardness, the

hardness of the reinforced Al7075/SiC nanocomposite was enhanced about 20% with respect to the monolithic material [28]. A fine and uniform particle distribution of SiC increased the yield strength, ultimate tensile strength, Young's modulus, density and hardness of the alloy. Addition of SiC particles above a critical value within the composites lowers the mechanical properties of the composite, which is due to the formation of SiC clusters [29]. Consistent dispersion of SiC particulates in the matrix alloy was observed in the optical micrographs of Al 7075/SiCp MMCs. T6 condition of heat treatment improved all the mechanical properties under consideration [30]. Presence of B_4C particles in Al6061 alloy accelerating the aging process and thus attain higher strength. These particles provide more sites for the nucleation of fine precipitates. These fine precipitates anchor lattice strain to deform the matrix to increase hardness and wear resistance of materials [31]. The T-6 heat treatment with an aging had a significant effect on wear resistance of composite [32]. Density, hardness and wear resistance of composites were improved with embedments of SiC and B_4C reinforcements [33, 34]. From the literature, it is obvious that the wear process and wear mechanism are varying with respect to the experiments even for the same reinforcing particles. Therefore a systematic and comparative investigations are essential to understand the wear mechanism of particle reinforced AMC. Moreover, the comparative analysis of wear behavior of SiC reinforced Al composite with B_4C reinforced Al composite is not studied in detail, especially at Al6063-T6 alloy.

In this work, an attempt has been made to study wear performance of SiC reinforced Al alloy and compared with B_4C reinforced Al alloy and unreinforced alloy. An ultrasonic stir cast method of producing Al + B_4C and Al + SiC composites with Al6063-T6 matrix was adopted with weight percentages of 3% of B_4C and 3% of SiC nano particles respectively. Variation of Frictional force(N) and Wear(μm) of Al 6063-T6, Al + B_4C and Al + SiC as a function of sliding distance is compared. SEM micrographs of worn out surface is studied. and wear mechanisms of the composites with different normal loads have been compared.

2 Experimental procedure

Al6063-T6 aluminum alloy was used as a matrix for preparing reinforced AMCs by stir casting technique. The reinforcements, SiC nanoparticles of average size ranging between 09 and 50 nm and B_4C nanoparticles of average size ranging between 40–60 nm. The SiC reinforced AMCs were synthesized by adding 3 wt. % of SiC nanoparticles as a reinforcement material using the stir-casting method. Initially, the Aluminum alloy was melted in a resistive

heating furnace at 680 °C. The melt was kept at 680 °C with a dwelling time of ten minutes to homogenize the melt. To prevent the oxidation of alloy the melting was performed under argon atmosphere. In the molten Aluminum alloy, 3 wt.% of SiC nanoparticles were added slowly for the preparation of nano SiC reinforced AMC. In general, the added nanoparticles tends to agglomerate at high temperature molten Al despite of stirring process. Hence, the nanoparticle added molten Al alloy was stirred ultrasonically for about 60 min at 100 °C above the melting temperature of aluminum for homogenized mixing of the reinforcement materials. After homogenization of the melt, the temperature of the melt was gradually increased and maintained at 850 °C for better flowability [12]. Subsequently, the composite melt was vertically filled in a one piece cylindrical shaped steel die with diameter 10 mm and height 50 mm, which is maintained at 500 °C to avoid rapid cooling and heterogeneity. The die with molten Al alloy was gradually cooled to room temperature and the solidified reinforced AMC was removed from the die for further analysis. The similar procedure was followed for the preparation of B₄C reinforced AMCs. The Al6063-T6 alloy was also prepared for comparative study.

The pure Al6063-T6 alloy and reinforced (Al + B₄C and Al + SiC) AMC specimens were characterized by various analytical techniques. Morphological properties of the AMC specimens were studied by Scanning Electron Microscope (SEM). The elemental composition of the AMC composite was studied by Electron probe micro analysis (EPMA) mapping and EDS analyses.

Pure Al6063-T6 alloy, Al + B₄C and Al + SiC composites were matted against EN31 steel disc (Hardened to 62HRC) (counter surface) for wear analysis. The specimens for the wear study were machined from the compacted samples in the form of cylindrical pin of 6 mm diameter and 30 mm height. The specimens were tested for sliding wear in a pin-on-disc test rig at dry condition. The wear test was carried out at a constant sliding velocity of 1 ms⁻¹ with three normal loads of 10 N, 20 N and 30 N for an identical sliding distance of 1000 m. After the wear, the surface morphology of the worn out surface of the samples were analysed by SEM to understand the wear mechanism. Moreover, the wearing process in Al6063-T6 alloy, Al + B₄C and Al + SiC were comparatively analyzed using the measured data and SEM images.

3 Results and discussion

3.1 Morphological and compositional analysis

The surface morphology of the B₄C and SiC nanoparticles are shown in Fig. 1a–d. As can be seen from the Fig. 1a,

b, the B₄C nanoparticles with the size in the range of 80–100 nm. Whereas, the SiC has plate like morphology as can be seen from Fig. 1c, d. Figure 2 shows the SEM image of Al6063-T6, Al + B₄C and Al + SiC samples at a lower magnification. The presence of reinforcing elements such as B₄C and SiC reduces stress during cooling of the stirred molding which results textured surface. EPMA mapping of Al6063-T6, Al + B₄C and Al + SiC samples for the reinforced elements were obtained by Field emission scanning electron microscope and the corresponding EDS spectra are shown in Figs. 3, 4 and 5, respectively. Very meager amount of respective reinforcing elements were seen in the images of mapping. However, the recorded EDS spectra confirm the presence of reinforcing materials as the related peaks were clearly observed in the EDS spectra. EDS analysis further confirms the presence of other element of oxygen in the aluminum alloy which may due to the formation of oxides. The elemental composition obtained from this study has been tabulated in Table 1, which confirms the reinforcement of boron, carbon silicon in the respective composites.

3.2 Wear behaviour

Figures 6, 7 and 8 show the variation of frictional force and wear (mass loss) of the Al6063-T6, Al + B₄C and Al + SiC samples as a function of sliding distance at different normal load of 10 N, 20 N and 30 N. As shown in the figures, for all the specimen, the wear is increases with increasing sliding distance. In Fig. 6, it is seen that the frictional force is relatively low for pure Al alloy compared to reinforced AMCs and has more wear compared to reinforced AMCs which shows the weak mechanical strength of the pure Al alloy. As can be seen from Fig. 6e, the frictional force of Al + SiC sample is nearly 1.7 times higher than that of pure Al alloy, however, the wear is decreased to 25% at the sliding distance of 1000 m compared to pure alloy. The frictional force of Al + B₄C sample is relatively increased with slight reduction in the wear rate compared to pure alloy (Fig. 6c, d). Moreover, several spikes were observed in the wear profile of the reinforced samples (Fig. 6d, f) which indicate the non steady sliding due to the presence of debris and particulates on the wearing surfaces.

The frictional force and the wear increases with increasing the normal load from 10 to 20 N for all the samples as can be seen from Fig. 7a–f. Further, the frictional force is relatively higher for Al + SiC sample compared to Al + B₄C and pure Al alloy. As a result, the Al + SiC exhibit low wear compared to other samples. In addition, large number of spikes was observed in the wear profile of all samples which shows the rapid wearing process under high normal loads and produces large number of debris and particles on the wearing surface.

Figure.1. SEM micrograph of **a, b** B_4C and **c, d** SiC nanoparticles

Fig. 2 SEM Images of **a** Al6063-T6, **b** Al + B_4C and **c** Al + SiC

The frictional force and wear rate further increases with increasing the normal load from 20 to 30 N for all the samples as shown in Fig. 8a–f. The rate of wear is relatively low in the Al + SiC sample compared to other samples despite of high frictional force (Fig. 8e, f). Moreover, the number of spikes is relatively larger with high intensity which is due to the formation of large number of debris and detached particles during the strong wearing process under high normal load.

From the Figs. 6, 7 and 8, it is seen that for all applied loads of 10 N, 20 N and 30 N the frictional force is relatively

higher for nanoparticles reinforced composites compared to pure Al alloy. The frictional force of all the samples increases with increasing normal loads. All the AMCs illustrate a reduction in wear with fewer spikes when increasing the sliding distance under various normal loads. The maximum wear of Al6063-T6 alloy, Al + B_4C and Al + SiC composites at the sliding distance of 1000 m are plotted as shown in Fig. 9a–c which has been measured as 80, 79 and 65 μm under 10 N normal load, 103, 90 and 80 μm under 20 N load and 120, 110 and 100 μm under 30 N load, respectively.

Fig. 3 SEM image with EPMA mapping of aluminum, carbon and oxygen elements (**a–d**) and corresponding energy dispersive spectrum (**e**) of Al6063-T6 sample

The variation of wear with respect to normal load at various sliding distance is plotted and shown in Fig. 10a–e. The wear increases with normal load for all the sliding distances. Moreover, the Al + SiC composite exhibit obviously low wear compared to Al + B₄C and pure Al alloy at all the sliding distance of 200, 400, 600, 800 and 1000 m. At shorter sliding distance the wear rate of Al + B₄C is slightly decreased compared with pure Al alloy whereas, at 1000 m of sliding distance, the wear is highly deviated from pure sample with low wear especially at higher loads. The Volume loss of Al 6063-T6, Al + B₄C and Al + SiC at 10 N, 20 N

and 30 N normal load for 1000 m distance recorded in the Table 2. Relatively, a significant improvement on wear properties of Al + SiC composite is recorded.

The high wear resistance for the reinforced AMCs is due to the increased friction force which is essential to overcome the shear force caused by adhesion between the friction pair surfaces under higher applied loads. Moreover, the friction heat causes surface oxidation to play a shielding effect and the material mixing rate is accelerated by atomic diffusion under a hot situation. In addition, the lattice distortion and dislocation induced by

Fig. 4 SEM image with EPMA mapping of aluminum, boron and carbon elements (**a–d**) and corresponding energy dispersive spectrum (**e**) of Al + B₄C sample

flexible deformation declines the wear even at higher friction forces. Furthermore, the high wear resistance of SiC reinforced AMCs are originated from the high interfacial binding strength between the Al and Si at the reinforced grain interfaces. Moreover, large number of Al–Si binding formation with high binding strength is quite feasible at the interface between Al matrix and reinforcing SiC nano sized grain. Therefore, the strength of Al increases when reinforcing with SiC nanoparticles. On the other hand, the binding strength of Al–B at the interface of Al matrix and B₄C grain is relatively weaker compared to Al–Si binding

due to smaller covalent radius of B than Si which results longer Al–B bond length and hence weaker binding strength. As a result, the reinforcing of B₄C in Al matrix exhibit relatively low wear resistance compared to Al + SiC AMCs.

3.3 Morphological study on wornout surfaces

SEM micrographs of worn out surfaces of the pure Al6063-T6 alloy, Al + SiC and Al + B₄C were recorded at different magnifications. The reinforcement distribution has been

Fig. 5 SEM image with EPMA mapping of aluminum, silicon and carbon elements (**a–d**) and corresponding energy dispersive spectrum (**e**) of Al + SiC sample

Table 1 Atomic and weight percentages of the elements present in the pure Al6063, Al + B₄C and Al + SiC of randomly selected region of the respective samples

Sample	Atomic percentage of elements					Weight percentage of elements				
	Al	B	C	O	Si	Al	B	C	O	Si
Al6063-T6	71.80	–	17.00	11.20	–	55.71	–	29.63	14.65	–
Al + B ₄ C	74.32	5.85	9.12	10.71	–	58.31	11.45	16.07	14.17	–
Al + SiC	77.47	–	13.05	8.72	0.76	63.38	–	23.99	12.03	0.6

observed as non-homogeneous in the SEM micrographs which may due to the density difference of the reinforcing materials with the aluminum matrix. The SEM micrographs of the wear tracks of the Al6063-T6 alloy, Al + SiC

and Al + B₄C under different loads are shown in Fig. 11a–i. As can be seen from the SEM images, the wear traces are clearly seen with the direction of wears. The wear traces are observed as darker layer which shows the formation of

Fig. 6 Variation of frictional force (N) and wear (μm) of Al 6063-T6 (a, b), Al+B₄C (c, d) and Al+SiC (e, f) as a function of sliding distance at 10 N Load

Fig. 7 Variation of frictional force (N) and wear (μm) of Al 6063-T6 (a, b), Al + B₄C (c, d) and Al + SiC (e, f) as a function of sliding distance at 20 N load

Fig. 8 Variation of frictional force (N) and wear (μm) of Al 6063-T6 (a, b), Al+B₄C (c, d) and Al+SiC (e, f) as a function of sliding distance at 30 N load

Fig. 9 Maximum wear (μm) of Al6063-T6, Al + B₄C and Al + SiC at 10 N (a), 20 N (b) and 30 N (c) normal load for 1000 m distance

narrow wear grooves and some micro cracks (Fig. 11a–i). Moreover, the wear traces are more stronger for the samples reinforced with nanoparticles compared to pure sample (Fig. 11a–c). The surface of pure sample is relatively smooth and adhesive with some furrow formations, while the SEM micrograph of Al + SiC and Al + B₄C shows relatively rough surfaces with some detached particles and strong wear grooves. Moreover, the bright area in SEM images show the heavy flow of materials along sliding direction which indicates a greater degree of wear and localized adhesion between the specimen surface and counter body. The wear traces with strong wear grooves are increases when the sample wears under higher normal loads (Fig. 11d–i). Moreover, the detached particles and debris are increases in the reinforced AMCs especially in the SiC reinforced sample and thus it shows high wear resistance compared to other samples as shown in Fig. 10.

The presence of Aluminum in the darker layer implies the transfer of aluminum from the pin to the worn surface

while the oxygen element predicates the oxidation reaction. These results imply that transfer and mechanical mixing of materials have taken place between the two sliding surfaces, and a mechanically mixed layer (MML) has formed in the darker areas on the worn surface. As a result, it seems that a mechanical mixing with oxidation process was responsible for wear resistance in the case of all composites [31].

The close view of the worn surfaces of Al + B₄C and Al + SiC is recorded by SEM with high magnification and shown in Figs. 12 and 13. It is seen that aluminum worn out from the surface with mild crest flattening scattered oxide debris of aluminum and discrete pull out of material. The bright oxide debris is not observed in the worn surface of Al + B₄C sample at 10 N load (Fig. 12a, b) and the debris and detached particles are observed in the sample at higher load. On the other hand, relatively large number of bright debris is observed in the Al + SiC at all the loads (Fig. 13a–f). Moreover, the detached particles, deep

Fig. 10 Variation of wear (μm) of Al 6063-T6, Al + B₄C and Al + SiC as a function of normal loads at 10 N, 20 N and 30 N for **a** 200 m, **b** 400 m, **c** 600 m, **d** 800 m and **e** 1000 m

Table 2 Volume loss of Al 6063-T6, Al + B₄C and Al + SiC at 10 N, 20 N and 30 N normal load for 1000 m distance

Load (N)	Volume loss (mm^3)		
	Al6063-T6	Al + B ₄ C	Al + SiC
10	2.2619	2.2337	1.8378
20	2.9123	2.5447	2.2619
30	3.3929	3.1102	2.8274

scratches are also seen with strong wear grooves and thus the Al + SiC sample exhibits high wear resistance.

The magnified SEM micrographs of worn out surfaces of the specimen Al + SiC and Al + B₄C shows deep scratches and bright debris on the worn surfaces, indicating that the main wear mechanism is abrasive wear with slight oxidation. Abrasive particles originate from the hard particles removed at the surface during friction. Figures 12 and 13 indicate that the wear

Fig. 11 SEM micrographs of worn out surfaces of the specimen Al6063+T6 [10 N (a), 20 N (d) and 30 N (g)], Al+SiC [10 N (b), 20 N (e) and 30 N (h)] and Al+B₄C [10 N (c), 20 N (f) and 30 N (i)]

track evolution on the worn surface at higher velocities shows three steps of wear process: abrasive, adhesive and oxidation. An oxide layer covered most of the area; however, abrasive traces were still observed, and some patches of material removal were found on the worn surfaces. Friction softened the hard particles, and oxidation protected the surface and diminished the abrasive wear. When the velocity remained at 1 m/s, under low load, the extent of abrasion scratches decreased and part of the surfaces were worn smooth, and oxidation became more significant. The evolution of the oxidation weakens the abrasive wear until abrasive scratches completely disappear with increasing load, the mode of

wear is a combination of oxidation and adhesive mechanisms. Changes in loads changed the wear mechanism from abrasive to oxidative and adhesive, depending on the magnitude of the temperature increase under dry sliding. Friction heat and oxidation play significant roles in changing the wear mechanism.

4 Conclusions

- The bulk nanocrystalline aluminum matrix composites with B₄C and SiC nanoparticles were produced by casting method with ultrasonication under stirring

Fig. 12 SEM micrographs of worn out magnified surfaces of the specimen Al + B₄C for 10 N (**a, d**), 20 N (**b, e**) and 30 N (**c, f**) loads

and the wear behavior of pure Al6063-T6, Al + SiC and Al + B₄C were comparatively investigated.

- The morphological properties of the AMC composites are analyzed by SEM. The composition of the composite and the presence of the reinforcing materials are confirmed by EPMA and EDS analyses.
- Al + SiC is highly wear resistant compared to other samples at all applied loads and Al–Si bond strength is responsible for the high wear resistance.
- The wear mechanism is varied from abrasive to oxidative by increasing the normal load as it was revealed from SEM images.

Fig. 13 SEM micrographs of worn out magnified surfaces of the specimen Al + SiC for 10 N (**a, d**), 20 N (**b, e**) and 30 N (**c, f**) loads

Compliance with ethical standards

Conflict of Interest The Authors declares that they have no conflict of interest.

References

1. Bermudez MD, Martinez-Nicolas G, Carrion FJ, Martinez-Mateo I, Rodriguez JA, Herrea EJ (2001) Dry and lubricated wear resistance of mechanically-alloyed aluminum base sintered composites. *Wear* 248:178–186
2. Haque MM, Sharif A (2001) Study on wear properties of aluminum–silicon piston alloy. *J Mater Proc Technol* 118:69–73
3. Harichandran R, Selvakumar N (2016) Effect of nano/micro B₄C particles on the mechanical properties of aluminium metal matrix composites fabricated by ultrasonic cavitation-assisted solidification. *Arch Civ Mech Eng* 16:147–158
4. Fisher TE, Anderson MP, Jahanmir S, Shlhei R (1988) Friction and wear of tough and brittle Zirconia in nitrogen, air, water, hexadecane and hexadecan containing stearic acid. *Wear* 124(2):133–148

5. Sasaki S (1989) The effects of surrounding atmosphere on friction and wear of alumina, zirconia, silicon nitride and silicon carbide. *Wear* 134:185–200
6. Sasaki SJ, Pethic B (2000) Effects of surrounding atmosphere on micro-hardness and tribological properties of sintered alumina. *Wear* 241:204–208
7. Ibrahim IA, Mohamed FA, Lavernia EJ (1991) Particulate reinforced metal matrix composites, a review. *Mater Sci* 26:1137–1156
8. Chiou JM, Chung DDL (1991) Characterization of MMC's fabricated by vacuum infiltration of a liquid metal under and inert gas pressure. *J Mater Sci* 26:2583–2589
9. Yang Y, Lan J, Li X (2004) Study on bulk aluminum matrix nano-composite fabricated ultrasonic dispersion of nano-sized SiC particles in molten aluminum alloy. *Mater Sci Eng, A* 380:378–383
10. Sahin Y (2003) Wear behavior of aluminum alloy and its composites reinforced by SiC particles using statistical analysis. *Mater Des* 24:95–103
11. Toptan F, Kilicarslan A, Karaaslan A, Cigdem M, Kerti I (2010) Processing and microstructural characterisation of AA 1070 and AA 6063 matrix B₄C p reinforced composites. *Mater Des* 31:S87–S91
12. Gahr KH, Schneider J (2000) Surface modification of ceramics for improved tribological properties. *Ceram Int* 26:363–370
13. Bai M, Xue Q, Wang X, Wan Y, Liu W (1995) Wear mechanism of SiC whisker reinforced 2024 aluminum alloy matrix composites in oscillating sliding wear tests. *Wear* 185:197–202
14. Alpas AT, Zhang J (1992) Effect of SiC particulate reinforcement on the dry sliding wear of aluminium-silicon alloys (A356). *Wear* 155(1):83–104
15. Sharifi EM, Karimzadeh F, Enayati MH (2011) Fabrication and evaluation of mechanical and tribological properties of boron carbide reinforced aluminum matrix nanocomposites. *Mater Des* 32(6):3263–3271
16. Poovazhagan L, Kalaichelvan K, Rajadurai A, Senthilvelan V (2013) Characterization of hybrid silicon carbide and boron carbide nanoparticles-reinforced aluminum alloy composites. *Procedia Engineering* 64:681–689
17. Ede SE, Odo JU, Adiele ID, Ani JN, Onyia CW, Okorie BA (2015) Effects of silicon carbide (SiC) nano particulates addition on mechanical properties of Aa2618 Alloy. *Int J Sci Res Publ* 5(4):1
18. Venkataraman B, Sundararajan G (1996) The sliding wear behaviour of Al–SiC particulate composites—I Macrobehaviour. *Acta Mater* 44(2):451–460
19. Al-Rubaie KS, Yoshimura HN, de Mello JDB (1999) Two-body abrasive wear of Al–SiC composites. *Wear* 233:444–454
20. Sahin Y (2003) Wear behaviour of aluminium alloy and its composites reinforced by SiC particles using statistical analysis. *Mater Des* 24(2):95–103
21. Yang Y, Lan J, Li X (2004) Study on bulk aluminum matrix nano-composite fabricated by ultrasonic dispersion of nano-sized SiC particles in molten aluminum alloy. *Mater Sci Eng: A* 380(1):378–383
22. Zhiqiang S, Di Z, Guobin L (2005) Evaluation of dry sliding wear behavior of silicon particles reinforced aluminum matrix composites. *Mater Des* 26(5):454–458
23. Toptan F, Kilicarslan A, Karaaslan A, Cigdem M, Kerti I (2010) Processing and microstructural characterisation of AA 1070 and AA 6063 matrix B₄C p reinforced composites. *Mater Des* 31:S87–S91
24. Lashgari HR, Sufizadeh AR, Emamy M (2010) The effect of strontium on the microstructure and wear properties of A356–10% B₄C cast composites. *Mater Des* 31(4):2187–2195
25. Kalaiselvan K, Murugan N, Parameswaran S (2011) Production and characterization of AA6061–B₄C stir cast composite. *Mater Des* 32(7):4004–4009
26. Jayashree PK, Shankar MG, Achutha K, Sharma SS, Raviraj S (2013) Review on effect of silicon carbide (SiC) on stir cast aluminium metal matrix composites. *Int J Curr Eng Technol* 3(3):1061–1071
27. Abhik R, Umasankar V, Xavier MA (2014) Evaluation of properties for Al–SiC reinforced metal matrix composite for brake pads. *Proc Eng* 97:941–950
28. Atrian A, Majzoobi GH, Enayati MH, Bakhtiari H (2014) Mechanical and microstructural characterization of Al7075/SiC nano-composites fabricated by dynamic compaction. *Int J Miner Metall Mater* 21(3):295–303
29. Balasubramanian I, Maheswaran R (2015) Effect of inclusion of SiC particulates on the mechanical resistance behaviour of stir-cast AA6063/SiC composites. *Mater Des* 1980–2015(65):511–520
30. Rana HG, Badheka VJ, Kumar A (2016) Fabrication of Al7075/b₄c surface composite by novel friction stir processing (FSP) and investigation on wear properties. *Proce Technol* 23:519–528
31. Das D, Mishra P, Chaubey A, Singh S (2016) Fabrication process optimization for improved mechanical properties of Al 7075/ SiCp metal matrix composites. *Manag Sci Lett* 6(4):297–308
32. Shankar G, Sharma SS, Kini A, Jayashree PK, Gurumurthy BM (2016) Study of wear behavior and mechanical mixed layer on artificial aged Al6061 composite reinforced with B₄C particles. *Query Indian J Sci Technol* 9(12):88073
33. Öksüz KE (2015) A study on Al₂O₃/SiC/B₄C reinforced cu-sn matrix composite by warm compaction powder metallurgy. *Adv Technol Mater Process* 1128:123–126
34. Öksüz KE, Şahin Y (2016) microstructure and hardness characteristics of Al₂O₃-B₄C particle-reinforced cu matrix composites. *Acta Phys Pol A* 129(4):650–652

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.