Springer

KSME

Journal of Mechanical Science and Technology 32 (2) (2018) 579~592
www.springerlink.com/content/1738-494x(Print)/1976-3824(Online)
DOI 10.1007/s12206-018-0105-5

Parametric study of the dry sliding wear behaviour of AA6082-T6/SiC and AA6082-T6/B_4C composites using RSM †

Gurpreet Singh[1,2,*], Sanjeev Goyal[1], Georgina Miranda[3] and Neeraj Sharma[4]

[1]*Department of Mechanical Engineering, YMCA University of Science and Technology, Faridabad, 121006, Haryana, India*
[2]*Amity Institute of Technology, Amity University, Noida, 201313, UP, India*
[3]*Center for Micro Electro Mechanical Systems (CMEMS-UMinho), University of Minho, Campus de Azurem, 4800-058, Guimaraes, Portugal*
[4]*Department of Mechanical Engineering, Maharishi Markandeshwar University, Mullana- 133207, India*

(Manuscript Received January 14, 2017; Revised November 8, 2017; Accepted November 14, 2017)

Abstract

In this paper a parametric study of the wear behaviour of Aluminum matrix composites has been carried out. AA6082-T6/SiC and AA6082-T6/B_4C composites were fabricated using stir casting technique. The percentage of reinforcement was taken as 5, 10, 15 and 20 wt.% for both SiC and B_4C particulates. Dry sliding wear tests were conducted using pin-on-disc apparatus at room temperature and process optimization was done using Response surface methodology (RSM). Weight percentage (wt.%) of reinforcement, sliding speed, load and sliding distance were the four process parameters considered to analyse these composites wear behaviour. Analysis of variance (ANOVA) showed that sliding distance exerted the highest contribution (60.24 %) to AA6082-T6/SiC wear, followed by sliding speed (14.28 %), load (11.88 %) and reinforcement content (4.31 %). The same trend was found in AA6082-T6/B_4C composites with slightly different contribution values, namely sliding distance (63.28 %), sliding speed (14.02 %), load (10.10 %) and reinforcement content (4.05 %). RSM analysis revealed that increases in the reinforcement content and sliding speed reduce the wear rate in both composites. On the other hand, increases in load and sliding distance led to higher AA6082-T6/SiC and AA6082-T6/B_4C composites wear. The two predictive models were validated by conducting confirmation tests and certified that the developed wear predictive models are accurate and can be used as predictive tools for wear apllications.

Keywords: AA6082-T6/SiC; AA6082-T6/B_4C; Wear behaviour; RSM; Predictive models

1. Introduction

Aluminum matrix composites (AMCs) have been used in several sectors like automobile and defence once they present several advantages like high specific strength, excellent workability and high thermal conductivity [1]. On the other hand, the hardness and wear resistance [1] of aluminium restricted AMCs use in certain engineering applications where wear performance is crucial. According to researchers, it is found that AMCs containing hard particles have higher wear resistance [2].

Hard particles like SiC, B_4C, TiC, Al_2O_3, Si_3N_4 and ZrO_2 have been used as reinforcements in AMCs, allowing to obtain superior mechanical properties but at the same time contributing to a wear increase as these hard particles can penetrate through the metal during sliding and dislodge material in the form of fragments [3]. This aspect influences the performance not only of the composite but above all of the tribological pair.

As abundantly reported in literature, several aspects regarding AMCs reinforced with SiC and B_4C have been studied. SiC has been extensively used as reinforcement for AMCs, finding application in pistons, cylinder heads, bearings and many other automotive components [4]. Due to its hardness, B_4C provides higher strength to aluminum-based composites and finds industrial applications in the nuclear field, automotive and army [5].

Kwok and Limb [6] investigated the tribological behaviour of Al-SiC composites and observed that the wear rate is enhanced when increasing sliding velocity and load. Also regarding Al-SiC composites wear, Sahin [7] investigated the influence of the sliding distance, load and particle size using a statistical approach and reporting that by increasing the sliding distance, load and particle size the wear rate in these composites escalates. Miranda et al. [8] evaluated the wear rate of AlSi/Ti/SiC composite sliding against gray cast iron, finding a significant wear rate reduction when comparing to the unreinforced AlSi. Girish et al. [9] conducted the statistical investigation on wear behaviour of magnesium alloy (AZ91) hybrid

*Corresponding author. Tel.: +91 964 672 6195
E-mail address: gurpreet.er85@gmail.com
† Recommended by Associate Editor Hak-Sung Kim

Table 1. Chemical composition of AA6082-T6 alloy.

Element	Al	Si	Mg	Mn	Fe	Zn	Cu	Cr	Ti	Vn
Content (wt.%)	97.40	0.91	0.69	0.56	0.23	0.098	0.06	0.035	0.019	0.01

metal matrix composites using Taguchi technique at different loads and sliding speeds and reported that normal had the highest influence on the wear rate followed by speed and reinforcement content. Rao et al. [10] fabricated SiC-reinforced aluminum composite through liquid metallurgy route and studied the microstructure, mechanical properties and dry sliding wear behaviour. Rao et al. [10] analysis was carried out varying the applied load at a uniform velocity and results showed that the composite had higher wear resistance and slightly lower coefficient of friction as compared to the unreinforced alloy. Shorowordi et al. [11] investigated the effect of sliding velocity on wear behaviour on Al-SiC and Al-B_4C composites against a brake pad and reported that lower wear rate and coefficient of friction was achieved at higher sliding velocity for both composites. Raja and Raja [12] produced an AMC based on A356 alloy reinforced with B_4C particles, by stir casting route, and after conducting wear tests observed that the wear rate of these composites increased when increasing load and B_4C content. In a similar study conducted by Attar et al. [13], B_4C reinforced AMC fabricated using Al-7025 matrix showed a lower wear rate than the unreinforced alloy. Baradeswaran and Perumal [14] also used B_4C to reinforce Al-7075 alloy and studied the composite wear behaviour, hardness and tensile strength. In this study, increases in hardness, tensile strength and wear resistance were observed with the addition of B_4C to the matrix. Baradeswaran and Perumal [14] observed the presence of a layer composed of iron and oxygen on the worn surface, which can play a significant role in controlling the wear rate. Canakci and Arslan [15] investigated the effect of volume fraction and particle size on the abrasive wear behaviour of Al2024 based composite reinforced with B_4C particles and observed a decrease in specific wear rate of the composite when increasing the volume fraction of B_4C particles. Furthermore, these authors reported that the wear rate of these composites decreases as the B_4C particle size increases.

Works found in literature show that the parametric study of AA6082-T6/SiC and AA6082-T6/B4C composites tribological behaviour is limited. In this sense, AMCs were fabricated by conventional stir casting technique using AA6082-T6 matrix and SiC and B_4C reinforcing particulates in order to analyse these two composites wear behaviour. This study intends to evaluate the influence of four parameters (Reinforcement content, sliding speed, sliding distance and load) on these composites wear performance. Additionally this work intends to assess how the effects of these process parameters differ on SiC and B_4C reinforced composites. Response surface methodology (RSM) was used for the planning of experiments and modelling of the four parameters, taking five levels of each parameter to study their influence on AA6082-T6/SiC and AA6082-T6/B4C composites wear behaviour. Confirmation tests validated the two predictive models that were developed.

Table 2. Details of SiC and B_4C particulates.

Reinforcement	Average particle size (µm)	Density (g/cm^3)	Melting point (°C)	Hardness (kg/mm^2)
SiC	35	3.20	2700	2800
B_4C	35	2.52	2450	3000

2. Experimental details

2.1 Materials

The matrix material adopted for the present work was commercially available AA6082-T6 and the chemical composition of the alloy is given in Table 1. AA6082 has good wear and corrosion resistance and the presence of magnesium and silicon makes it a significant strong and hard alloy [16]. The reinforcement particles selected for the fabrication of the composites were SiC and B_4C with an average size of 35 micrometers. SiC particulates form excellent bonding with molten matrix and show adequate thermal conductivity and machinability which makes it one of the most preferred reinforcements for composites [17, 18]. The high cost of B_4C as compared to the majority of commercially used reinforcements has limited its use in composite fabrication [19]. However, B_4C has advantageous properties such as high stiffness, hardness and low density (Even lower than some aluminum alloys) which make it an alluring reinforcement material. The details of SiC and B_4C particulates used in this work are given in Table 2.

2.2 Composites fabrication

Conventional stir casting technique was used to fabricate AA6082-T6/SiC and AA6082-T6/B_4C composites. Selvi and Rajasekar [20] also fabricated Aluminium composites through stir casting technique for their wear characterization using RSM. In present work, one kilogram of the aluminum alloy was cut in small rectangular sheets with 6 mm thickness and put into a graphite crucible. The crucible was heated in an electric furnace for 2-3 hours, until the temperature reached 800-850 °C, in order to melt the aluminum completely. Magnesium was added (1 wt.%) to the matrix alloy in order to promote a strong bonding between the matrix and the particulates [21]. The reinforcement particles were preheated in a microwave oven for 1-2 hours at 300 °C approximately, in order to eliminate any eventual moisture content [22]. The preheated reinforcement particles were added into the molten matrix and the slurry was continuously stirred at 400 rpm with the help of a graphite stirrer, to attain a homogeneous mixture. After 12-15 minutes of continuous stirring, the molten mixture was poured in a sand mould with dimensions of 300 mm in length, 80 mm width and 40 mm depth. The material was then

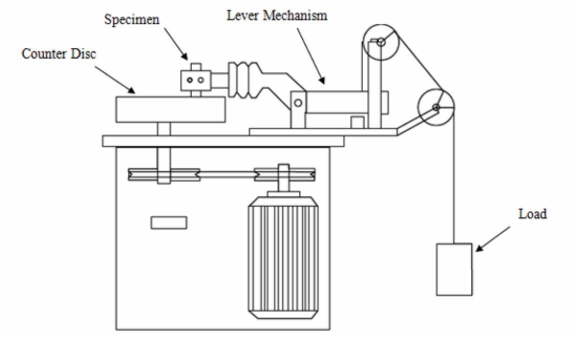


Fig. 1. Drawing of the pin on disc apparatus used for present work.

allowed to cool down and solidify before being separated from the sand mould.

In the present work, all the AA6082-T6/SiC and AA6082-T6/B_4C composites samples were prepared using the same method as discussed above and using the following SiC and B_4C particulates additions: 5, 10, 15 and 20 wt.%.

2.3 Microstructure analysis

Cylindrical samples with 6 mm diameter and 20 mm height were machined from the fabricated composites in order to analyse the microstructure using optical (Eclipse MA-100, Nikon) and scanning electron (JOEL, JSM-6510LV) microscopes. The samples were polished with emery paper of grade 200, 400 and 600 and etched with Keller's reagent containing 2 ml HF, 3 ml HCl, 20 ml HNO_3 and 175 ml H_2O.

X-ray diffraction (XRD) patterns were recorded using PANalytical X'pert PRO X-ray diffractometer. The diffractometer was equipped with graphite curved single crystal monochromator to select CuK radiation $(\lambda = 1.54\dot{A})$ at the goniometer receiving slit station. Angle of 20º to 110º for diffraction angle (2θ) was maintained during XRD analysis.

2.4 Micro-hardness analysis

Micro-hardness of AA6082-T6/SiC and AA6082-T6/B_4C composites were measured using a Vickers hardness tester using IS 1501-2002 test method by applying a load of 1 kg on each sample for 15 seconds [23]. Each sample was tested three times and the average value was taken.

2.5 Wear tests

Pin-on-disc tests were performed using cylindrical pins machined from the fabricated AA6082-T6/SiC and AA6082-T6/B_4C composites and also from the unreinforced alloy, with 6 mm diameter and 35 mm height. The pins surface were polished using 200, 400 and 600 mesh paper. EN31 steel disc (with hardness of 720 HV and surface roughness of 0.1 µm) was used as counter surface. A drawing view of the set-up used in the present work is shown in Fig. 1.

The pin was held stationary against the rotating steel disc and with the help of a lever mechanism a normal load was applied. The tests were performed at room temperature (30-35 ºC) and relative humidity of 25-35 %. The dry sliding wear behaviour of the composites and of the unreinforced alloy was assessed by measuring the weight loss of each pin after every run, using an accuracy of 0.0001 g.

Table 3. Factors and levels used in the CCD experimental plan.

		Levels				
Factors	Designation	-2	-1	0	1	2
Reinforcement (wt.%)	R	0	5	10	15	20
Sliding speed (m/s)	S	0.6	1.2	1.8	2.4	3.0
Load (N)	L	14.71	29.42	44.13	58.84	73.55
Sliding distance (m)	D	400	800	1200	1600	2000

2.6 Response surface methodology (RSM)

The addition of SiC or B_4C particulates as reinforcements to aluminium alloys generally leads to a hardness enhancement, as proven by several studies [24-26]. In view of this, several reinforcement weight percentages were selected as one of the process parameters, along with load, sliding speed and sliding distance. Table 3 shows these process parameters along with the five levels of each parameter, selected for the present work. In the present work, Response surface methodology with Central composite design (CCD) was used to plan and analyze the design of experiments. The Central composite design (CCD) contains factorial points each at upper (+1) and lower (-1) values, center points (0) and axial points of upper (+2) and lower (-2) values. In this way, there are five levels of each process parameters in CCD. CCD is also an efficient tool for building quadratic models consisting of a number of factors [27]. Another advantage of CCD plan is that it can be employed to study factors with high number of levels and that it allows lesser number of tests [28].

The experimental plan as suggested by RSM is shown in Table 4 with coded and actual values of the four parameters along with the results obtained in weight loss.

3. Results and discussion

3.1 Micro structural evaluation

SEM images of AA6082-T6/SiC and AA6082-T6/B_4C composites, with 5, 10, 15 and 20 wt.% of reinforcement are shown in Figs. 2(a)-(d) and 3(a)-(d), respectively. These images show a relatively good dispersion of SiC and B_4C particles in the respective composites. However, when increasing the reinforcement content from 5 to 20 wt.%, particles clusters were observed, for both AA6082-T6/SiC and AA6082-T6/B4C composites. Still, in AA6082-T6/SiC composites, SiC particles seemed more prone to agglomeration, possibly

Table 4. Details of test combinations in coded and actual values of factors and corresponding experimental results.

Run No.	R	S	L	D	% Reinforcement, R	Speed, S	Load, L	Sliding distance, D	Wear Al-SiC (g)	Wear Al-B_4C (g)
1	-1	-1	-1	-1	5	1.2	29.42	800	0.0084	0.0073
2	1	-1	-1	-1	15	1.2	29.42	800	0.0066	0.0061
3	-1	1	-1	-1	5	2.4	29.42	800	0.0041	0.0039
4	1	1	-1	-1	15	2.4	29.42	800	0.0033	0.0031
5	-1	-1	1	-1	5	1.2	58.84	800	0.0111	0.0099
6	1	-1	1	-1	15	1.2	58.84	800	0.0087	0.0071
7	-1	1	1	-1	5	2.4	58.84	800	0.0082	0.0072
8	1	1	1	-1	15	2.4	58.84	800	0.0047	0.0036
9	-1	-1	-1	1	5	1.2	29.42	1600	0.0189	0.0152
10	1	-1	-1	1	15	1.2	29.42	1600	0.0148	0.0126
11	-1	1	-1	1	5	2.4	29.42	1600	0.0113	0.0103
12	1	1	-1	1	15	2.4	29.42	1600	0.0085	0.0075
13	-1	-1	1	1	5	1.2	58.84	1600	0.0231	0.0195
14	1	-1	1	1	15	1.2	58.84	1600	0.0181	0.0179
15	-1	1	1	1	5	2.4	58.84	1600	0.0197	0.0173
16	1	1	1	1	15	2.4	58.84	1600	0.0139	0.0121
17	-2	0	0	0	0	1.8	44.13	1200	0.0119	0.0107
18	2	0	0	0	20	1.8	44.13	1200	0.0106	0.0089
19	0	-2	0	0	10	0.6	44.13	1200	0.0163	0.0141
20	0	2	0	0	10	3	44.13	1200	0.0081	0.0069
21	0	0	-2	0	10	1.8	14.71	1200	0.0066	0.0061
22	0	0	2	0	10	1.8	73.55	1200	0.0147	0.0109
23	0	0	0	-2	10	1.8	44.13	400	0.0021	0.0017
24	0	0	0	2	10	1.8	44.13	2000	0.0193	0.0174
25	0	0	0	0	10	1.8	44.13	1200	0.0088	0.0084
26	0	0	0	0	10	1.8	44.13	1200	0.0087	0.0084
27	0	0	0	0	10	1.8	44.13	1200	0.0084	0.0072
28	0	0	0	0	10	1.8	44.13	1200	0.0102	0.0087
29	0	0	0	0	10	1.8	44.13	1200	0.0089	0.0075
30	0	0	0	0	10	1.8	44.13	1200	0.0077	0.0077

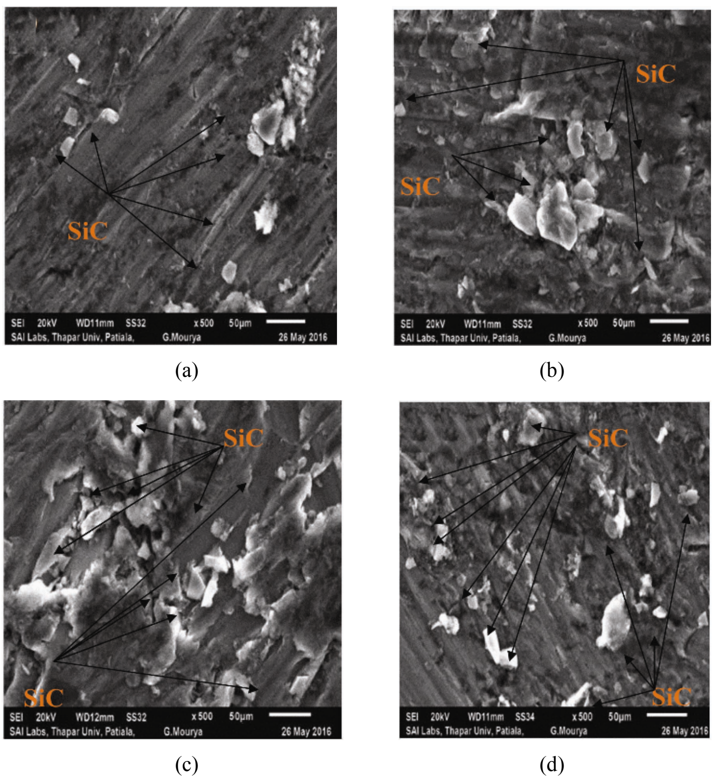


Fig. 2. SEM micrographs for (a) 5 %; (b) 10 %; (c) 15 %; (d) 20 % of SiC-reinforced AA6082-T6 composites.

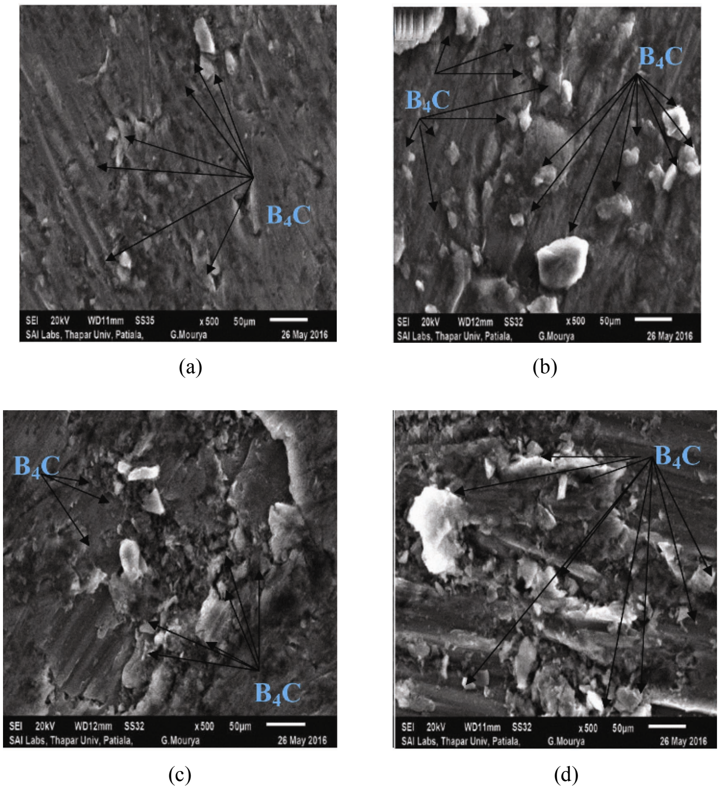


Fig. 3. SEM micrographs for (a) 5 %; (b) 10 %; (c) 15 %; (d) 20 % of B_4C-reinforced AA6082-T6 composites.

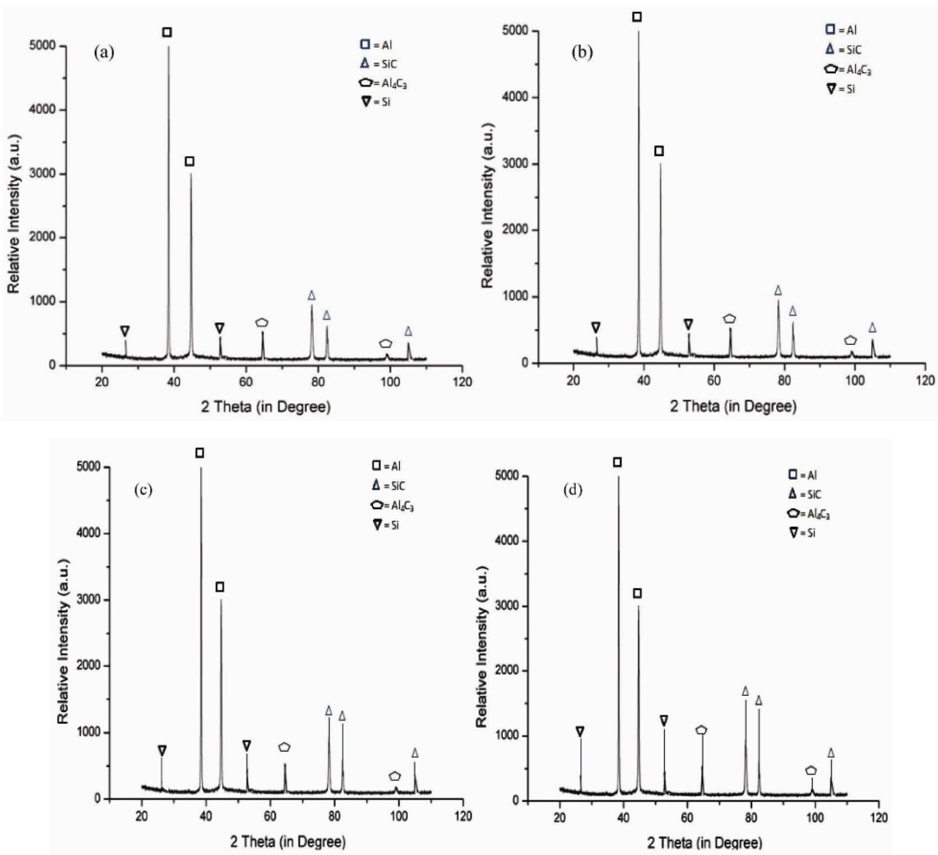


Fig. 4. XRD patterns for (a) 5 %; (b) 10 %; (c) 15 %; (d) 20 % of SiC-reinforced AA6082-T6 composites.

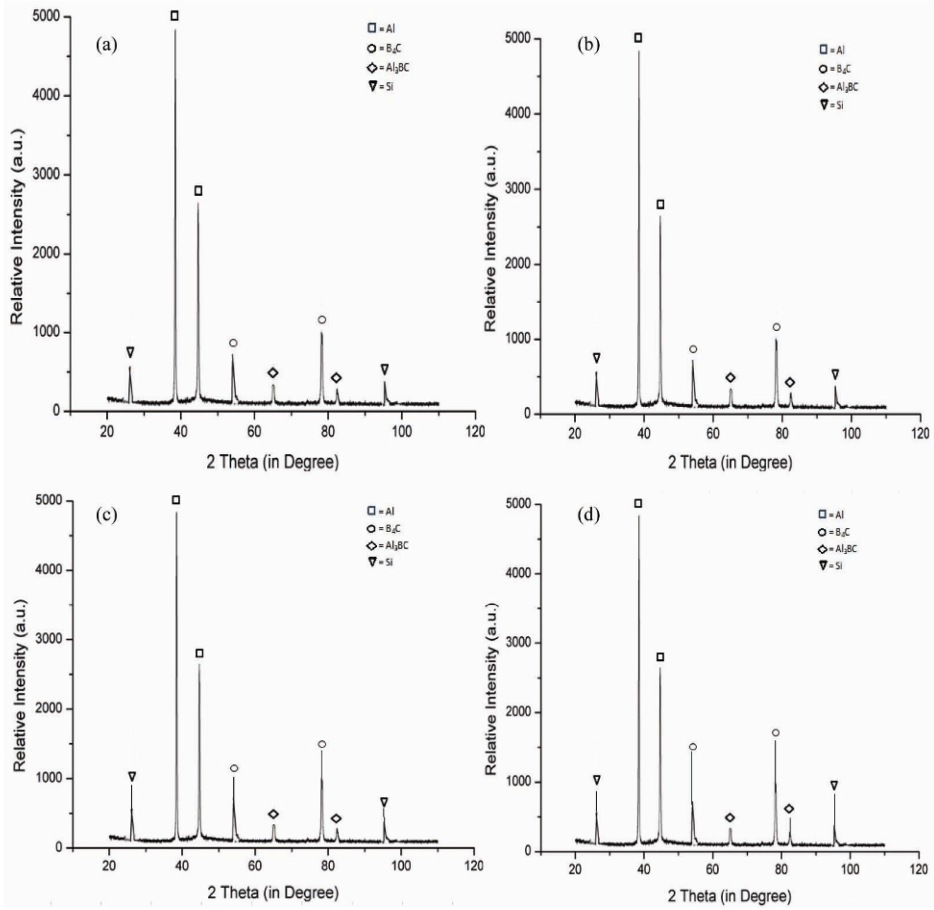


Fig. 5. XRD patterns for (a) 5 %; (b) 10 %; (c) 15 %; (d) 20 % of B_4C-reinforced AA6082-T6 composites.

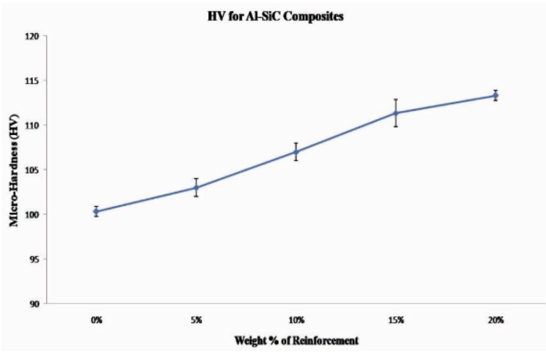
due to the high density of SiC (3.20 g/cm^3) when compared with aluminum (2.67 g/cm^3). Nevertheless, reinforcements agglomeration can contribute towards strengthening of a composite, if they are well bonded in the matrix [29]. The produced AA6082-T6/SiC and AA6082-T6/B4C composites revealed absence of voids at the interface, indicating a good interfacial bonding between particles and matrix.

X-Ray diffraction (XRD) patterns of the AA6082-T6/SiC and AA6082-T6/B_4C composites are shown in Figs. 4(a)-(d) and 5(a)-(d), respectively. XRD patterns of AA6082-T6/SiC composites revealed the presence of Al, SiC, Al_4C_3 and Si in the fabricated samples. In AA6082-T6/B4C composites presence of B_4C and Al_3BC was observed along with Al and Si. However, the peaks for Al_4C_3 and Al_3BC were small in the respective composites. In a study conducted by Vazquez et al. [30], it was reported that the phase Al_4C_3 can be obtained in most of the composites reinforced with carbides including SiC, TiC and B_4C. Production of Al_4C_3 has adverse effect on the aluminum composites because it readily reacts with water or the moisture present in the atmosphere and form aluminum hydroxide ($Al(OH)_3$), which degrades the quality of the composites. No technique can completely restrict the formation of Al_4C_3 in composites reinforced with carbides; however, its formation can be reduced by coating the reinforcements with SiO_2 [31], optimizing the process parameters [32] or modifying the chemical composition of the aluminum matrix [31]. Viala et al. [33] also observed the presence of Al_4C_3 and Al_3BC in the microstructure of aluminium composites.

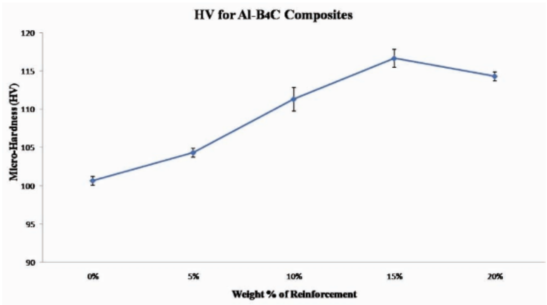
3.2 Composites micro-hardness

Micro-hardness evaluation has been carried out on the fabricated composites and un-reinforced alloy to determine the effect of reinforcement addition in the metal matrix. AA6082-T6/SiC and AA6082-T6/B_4C composites hardness results are given in Figs. 7(a) and (b), respectively.

Figs. 6(a) and (b) show that AA6082-T6/B_4C composites attain higher hardness values as compared to AA6082-T6/SiC. Results show that the gradual increase in the reinforcement content tends to increase the hardness of the composites. This outcome is mainly attributed to the higher hardness of SiC (285 HV) and B_4C (305 HV) particles used in this work, which contributes towards resisting plastic deformation, thus leading to higher hardness. The measured micro-hardness of the un-reinforced alloy was calculated as 101 HV. SiC additions led to a gradual increase in hardness, with the highest value (112 HV) being attained with 20 wt.% SiC. Similar observation was reported by Sahin [34] in his research work.



(a)



(b)

Fig. 6. Micro-hardness for (a) AA6082-T6/SiC; (b) AA6082-T6/B_4C composites, with varying weight percentages of SiC and B_4C.

B_4C additions led to higher hardness than that displayed by the matrix, but the highest value was 117 HV, obtained when adding 15 wt.% B_4C to the aluminium matrix.

A slight decrease in AA6082-T6/B_4C composites hardness was observed with 20 wt% addition of B_4C. This decrease in hardness can be related with the formation of B_4C clusters within the metal matrix, which can lead to hardness lowering. Poovazhagan et al. [35] also observed fluctuations in the hardness of the composites due to reinforcing particles agglomeration.

3.3 Analysis of variance (ANOVA) for wear behaviour

ANOVA was used to investigate the effect of process parameters on wear rate and to check the competency of the present model. ANOVA results using Central composite design (CCD) for AA6082-T6/SiC and AA6082-T6/B_4C composites are given in Tables 5 and 6. The results were evaluated with a confidence level of 95 % or p-value 0.05 suggesting any factor or their interaction with p-value less than 0.05 is significant as indicated by the right most columns in ANOVA Tables. Any factor or interaction which is non-significant (p-value > 0.05) was excluded from the analysis. The ANOVA results for both the composites shows the four process parameters i.e.% reinforcement (R), sliding speed (S), load (L) and sliding distance (D) as significant since p value for all the factors comes out to be less than 0.05. The quadratic terms of reinforcement, sliding speed, sliding distance and the interaction between load and sliding distance (L*D) were also found as significant in the present work. The only difference between the models obtained for the two composites was the presence of the quadratic term of load as significant factor in ANOVA analysis of AA6082-T6/SiC composites, which was

Table 5. Analysis of variance for wear of AA6082-T6/SiC composites.

Source	SS	DF	MS	F-Value	p-value	
Model	0.000769488	9	8.55E-05	54.62154	< 0.0001	S
R	0.00003456	1	3.46E-05	22.07895	0.0001	S
S	0.000114407	1	0.000114	73.08968	< 0.0001	S
L	9.52017E-05	1	9.52E-05	60.8204	< 0.0001	S
D	0.000482407	1	0.000482	308.1896	< 0.0001	S
L*D	7.5625E-06	1	7.56E-06	4.831368	0.0399	S
R^2	1.1963E-05	1	1.2E-05	7.64265	0.012	S
S^2	2.21144E-05	1	2.21E-05	14.12798	0.0012	S
L^2	7.14583E-06	1	7.15E-06	4.565177	0.0452	S
D^2	7.50012E-06	1	7.5E-06	4.791515	0.0406	S
Residual	3.13058E-05	20	1.57E-06	-	-	S
Lack of fit	2.79575E-05	15	1.86E-06	2.783225	0.1317	NS
Pure error	3.34833E-06	5	6.7E-07	-	-	-
Cor total	0.000800794	29	-	-	-	-
Std. Dev.	1.251E-003	R-squared			0.9609	
Mean	0.011	Adj R-squared			0.9433	
C.V. %	10.02	Pred R-squared			0.8954	
Press	8.374E-005	Adeq precision			27.705	

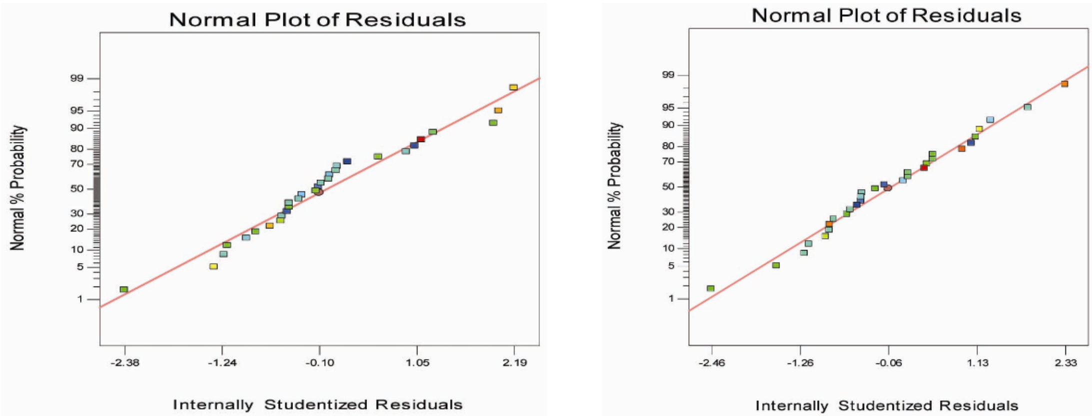
S: Significant; NS: Non-significant; SS: Sum of square; DF: Degree of freedom; MS: Mean square

Table 6. Analysis of variance for wear of AA6082-T6/B_4C composites.

Source	SS	DF	MS	F-value	p-value	
Model	0.000582672	8	7.28E-05	80.3035	< 0.0001	S
R	2.44017E-05	1	2.44E-05	26.90418	< 0.0001	S
S	0.000084375	1	8.44E-05	93.02809	< 0.0001	S
L	6.08017E-05	1	6.08E-05	67.03719	< 0.0001	S
D	0.000380807	1	0.000381	419.8603	< 0.0001	S
L*D	1.19025E-05	1	1.19E-05	13.12316	0.0016	S
R^2	0.000007	1	0.000007	7.717886	0.0113	S
S^2	1.27575E-05	1	1.28E-05	14.06585	0.0012	S
D^2	5.35938E-06	1	5.36E-06	5.909006	0.0241	S
Residual	1.90467E-05	21	9.07E-07	-	-	S
Lack of fit	1.72583E-05	16	1.08E-06	3.015785	0.1135	NS
Pure error	1.78833E-06	5	3.58E-07	-	-	-
Cor total	0.000601719	29	-	-	-	-
Std. Dev.	9.524E-004	R-squared		0.9683		
Mean	9.507E-003	Adj R-squared		0.9563		
C.V. %	11.52	Pred R-squared		0.9213		
Press	4.736E-005	Adeq precision		32.878		

Table 7. Percentage contribution of main parameters, interaction and quadratic effects affecting wear of AA6082-T6/SiC and AA6082-T6/B4C composites.

Factor	Reinforcement (R)	Sliding speed (S)	Load (L)	Sliding distance (D)	L*D	R^2	S^2	L^2	D^2	Others	Error
AA6082-T6/SiC	4.31	14.28	11.88	60.24	0.94	1.49	2.76	0.89	0.93	3.9	0.41
AA6082-T6/B_4C	4.05	14.02	10.1	63.28	1.97	1.16	2.12	NA	0.89	3.16	0.29



(a) (b)

Fig. 7. Normal plot of residuals for (a) AA6082-T6/SiC; (b) AA6082-T6/B4C models.

not found to be significant in AA6082-T6/B_4C composites. In both the SiC and B_4C reinforced composites, the value of R-squared was greater than adjusted R-squared which is adequate for a good model.

This is because R-squared explains the variability of the model due to significant and non-significant factors whereas adjusted R-squared includes significant terms only. ANOVA shows the Wear models for both the composites as 'Significant' and lack of fit as 'Not-significant' which are desirable from model point of view. These models adequacy can also be assured by analysing their adequate precision, which must be greater than 4 for a good model. In the present work, adequate precision values of 27.705 and 32.878 for SiC and B_4C reinforced composites were obtained, respectively. The percentage contribution of each process parameter was calculated by dividing the sum of squares of each factor with total sum of squares and is given in Table 7. It was found that for AA6082-T6/SiC composites, the contribution of sliding distance was maximum (60.24 %) followed by sliding speed (14.28 %), load (11.88 %) and reinforcement (4.31 %). Similar trend was observed in AA6082-T6/B_4C with slightly different values for contributions of sliding distance (63.28 %), sliding speed (14.02 %), load (10.10 %) and reinforcement (4.05 %). The contribution of interaction and quadratic terms was also calculated and shown in the same table.

Eqs. (1) and (2) represent the final equations in terms of coded factors which will be used further to explain the effect of the selected variables on wear (Weight loss).

Equation for AA6082-T6/SiC in terms of coded factors:

$$\text{Wear} = +8.783E\text{-}003 - 1.200E\text{-}003 * R - 2.183E\text{-}003 * S +1.992E\text{-}003 * L + 4.483E\text{-}003 * D + 6.875E\text{-}004 * L * D +6.604E\text{-}004 * R^2 + 8.979E\text{-}004 * S^2 + 5.104E\text{-}004 * L^2 + 5.229E\text{-}04 * D^2. \quad (1)$$

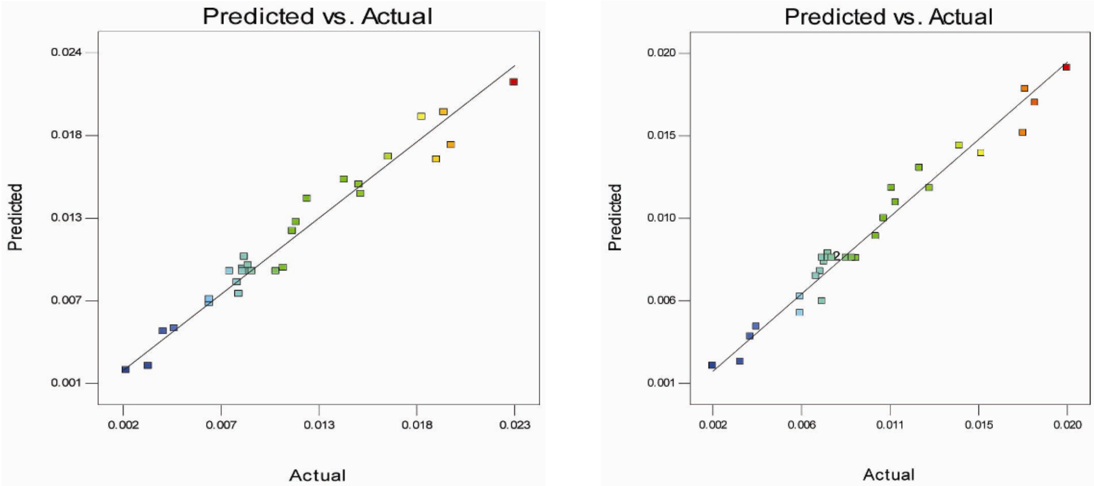
Equation for AA6082-T6/ B_4C in terms of coded factors:

$$\text{Wear} = + 8.217E\text{-}003 - 1.008E\text{-}003 * R - 1.875E\text{-}003 * S + 1.592E\text{-}003 * L + 3.983E\text{-}003 * D + 8.625E\text{-}004 * L * D + 5.000E\text{-}004 * R^2 + 6.750E\text{-}004 * S^2 + 4.375E\text{-}004 * D^2. \quad (2)$$

Figs. 7(a) and (b) show the normal plot of residual for AA6082-T6/SiC and AA6082-T6/B_4C composites and it can be seen that all the residuals are aligned along the inclined line which certifies normal distribution of ANOVA. Almost similar trend was followed in predicted vs actual plots as shown in Figs. 8(a) and (b). The graph of residuals versus predicted for the two composites are shown in Figs. 9(a) and (b) where the prediction made by the model is on the x-axis and the accuracy of that prediction is on the y-axis. The distance from line zero shows how bad the prediction is for that value. Positive values of residuals on the y-axis mean that the prediction was too low; whereas negative values mean that the prediction was too high. A scattered graph of residual vs. predicted considers to be an ideal graph [36].

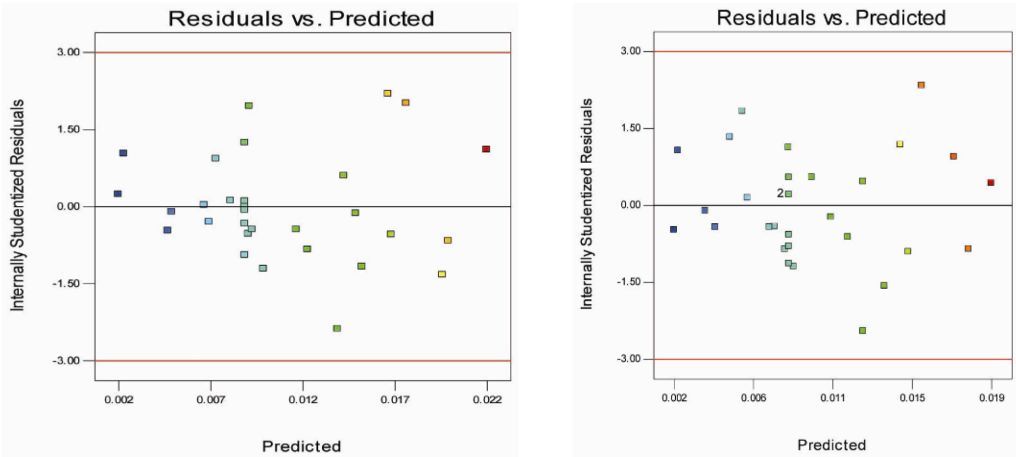
3.4 Variables effect on wear behaviour

The effect of variables or process parameters on dry sliding



(a) (b)

Fig. 8. Predicted vs actual plots for (a) AA6082-T6/SiC; (b) AA6082-T6/B4C models.



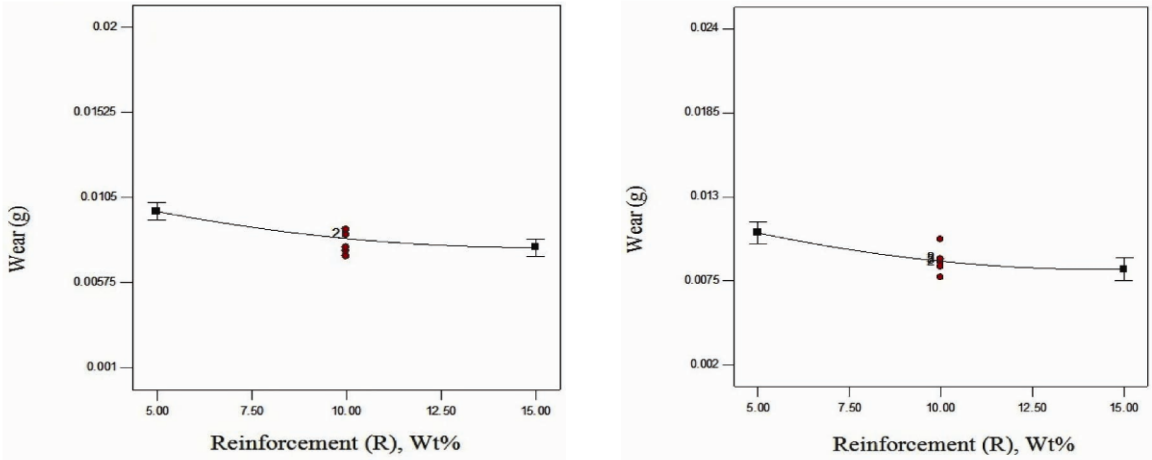
(a) (b)

Fig. 9. Residual vs predicted plots for (a) AA6082-T6/SiC; (b) AA6082-T6/B4C models.

wear behaviour of AA6082-T6/SiC and AA6082-T6/B_4C composites are given in Eqs. (1) and (2) in terms of coded values. The coefficients -0.0012 and -0.001008 associated with reinforcement content have negative values in both the equations which suggests that the reinforment addition to the metal matrix decreases the wear in these composites. This is related with the composites micro-hardness, as the addition of reinforcement enhances hardness, which lowers the material removal rate [37]. Therefore reinforcement addition performs a significant role in controlling the wear of the material.

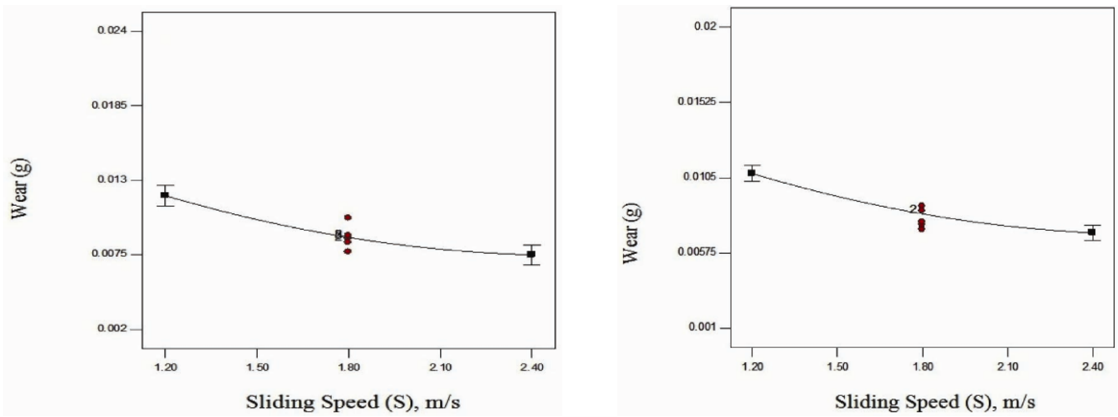
Figs. 10(a) and (b) show the variation of wear with addition of reinforcement in both the composites. Similar trend was observed with sliding speed, as the negative coefficients -0.002183 and -0.001875 represent decrease in wear with increasing sliding speed as also shown in Figs. 11(a) and (b).

As the negative values are higher in case of sliding speed as compared to % reinforcement, this signifies that sliding speed has more detrimental effect than the reinforcement on the wear of AA6082-T6/SiC and AA6082-T6/B_4C composites. The possible reason behind the wear reduction due to sliding speed is the change in shear rate (Due to changing speed), which disturbs the mechanical behaviour of the two surfaces in contact while sliding [38]. The strength of a material is higher at greater shear strain rates, thus resulting in lower contact area and consequeltly lesser wear [39, 40]. Moreover, the positive coefficients 0.001992 and 0.001592 in Eqs. (1) and (2), associated with load, indicate that a gradual increase in load increases the wear in these composites, which was also revealed by the Figs. 12(a) and (b). The wear increases with increasing load because load determines the deformation and pressure applied in the two surfaces in contact. By increasing load, higher pressure is applied at the mating surfaces, which causes greater deformation and results in higher material removal. The effect of load on the wear is however less as compared to sliding speed and sliding diatance. Regarding the sliding distance, the positive coefficient values 0.004483 and



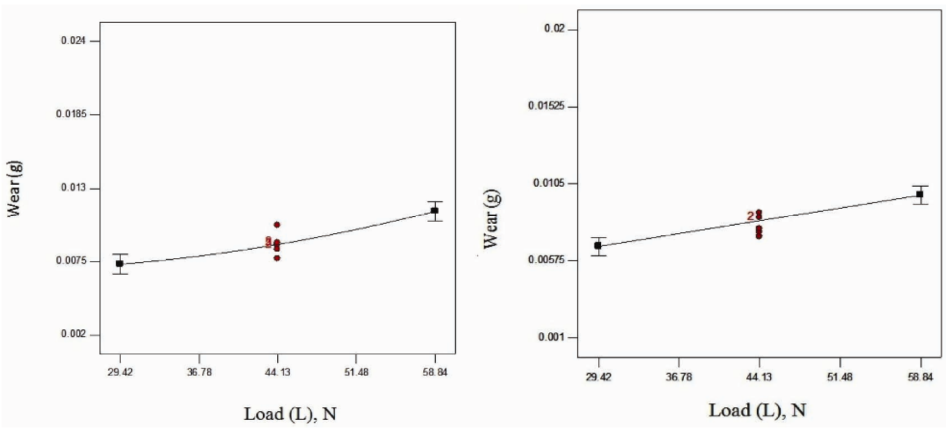
(a) (b)

Fig. 10. Variation in wear (Weight loss) with addition of reinforcement in (a) AA6082-T6/SiC; (b) AA6082-T6/B_4C composites.



(a) (b)

Fig. 11. Variation in wear (Weight loss) with increasing sliding speed in (a) AA6082-T6/SiC; (b) AA6082-T6/B_4C composites.

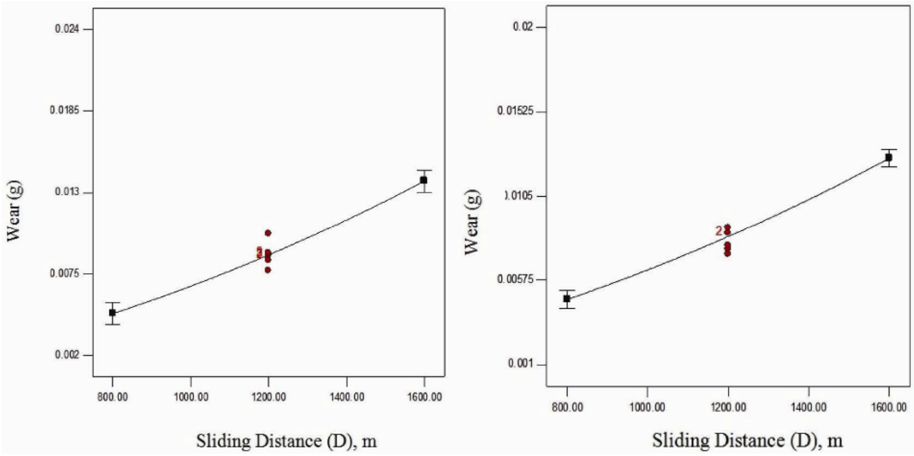


(a) (b)

Fig. 12. Variation in wear (Weight loss) with increasing load in (a) AA6082-T6/SiC; (b) AA6082-T6/B_4C composites.

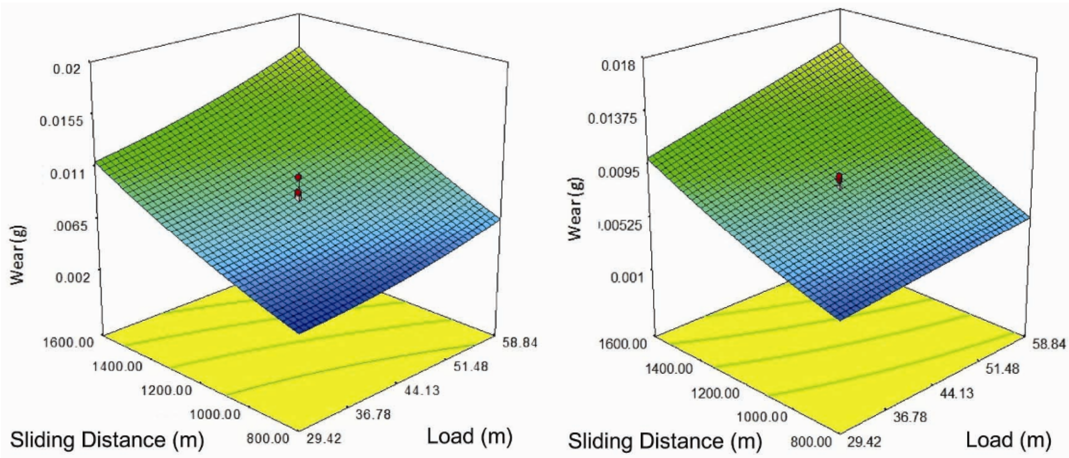
0.003983 for SiC and B_4C reinforced composites, respectively, are relativey high which suggests that sliding speed has a more detrimental effect on wear.

The increment in sliding distance increases the contact time between the pin and the counter surface which in turn enhances wear. The variation in wear in both the composite materials due to increase in sliding distance is shown in Figs. 13(a) and (b). ANOVA results suggest that in AA6082-



(a) (b)

Fig. 13. Variation in wear (Weight loss) with increasing sliding distance in (a) AA6082-T6/SiC; (b) AA6082-T6/B_4C composites.



(a) (b)

Fig. 14. 3D interaction plot between load (L) and sliding distance (D) against wear in (a) AA6082-T6/SiC; (b) AA6082-T6/B_4C composites.

T6/SiC and AA6082-T6/B_4C composites, the interaction between Load and sliding distance (L*D) is the only significant interaction. Figs. 14(a) and (b) show the 3-D interaction between load and sliding distance for the two composites, being clear that the maximum weight loss value attained in SiC reinforced composites is slightly higher than the maximum value obtained in B_4C reinforced composites. This can suggest that wear in AA6082-T6/SiC composites is higher than in AA6082-T6/B4C composites. In both the 3-D interactions it was evident that sliding distance was the predominant factor in increasing the wear, mainly due to the increase in interaction time between the pin and counter surface. Wear increases at lower and higher applied loads (29.42 N and 58.84 N) with escalation in the sliding distance. As the incremental load leads to higher pressure on the contacting surfaces, a high removal of material occurs. Fig. 14 shows that the minimum wear was attained at lower values of load and sliding distance for both composites and the combined effect of load and sliding distance enhances wear in these composites.

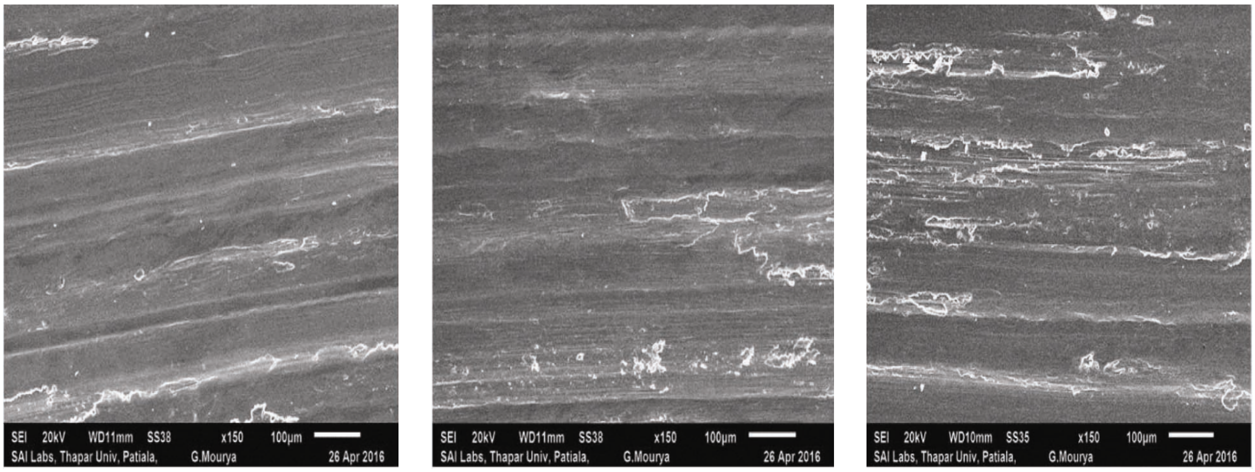
3.5 Confirmation tests

The final step in the wear behaviour analysis of AA6082-T6/SiC and AA6082-T6/B_4C composites was to validate the developed models and for this purpose, two confirmation tests were carried out by selecting different set of process parameters as shown in Table 8. SEM micrographs of the worn surfaces of SiC and B_4C reinforced composites that were tested for confirmation are shown in Figs. 15(a)-(c) and 16(a)-(c), respectively. The micrographs ofthe worn surfaces of the pins have one feature in common and that was the formation of parallel lines representing wear tracks in the sliding direction which eventually gets crushed off to become debris. Three confirmation tests were performed on both SiC and B_4C reinforced composites and weight loss comparison was done between the obtained experimental results and the predicted results by using the developed quadratic models (Table 9).

As shown in Table 9, the differences between experimental and predicted results were found to be below 7.5 % in both

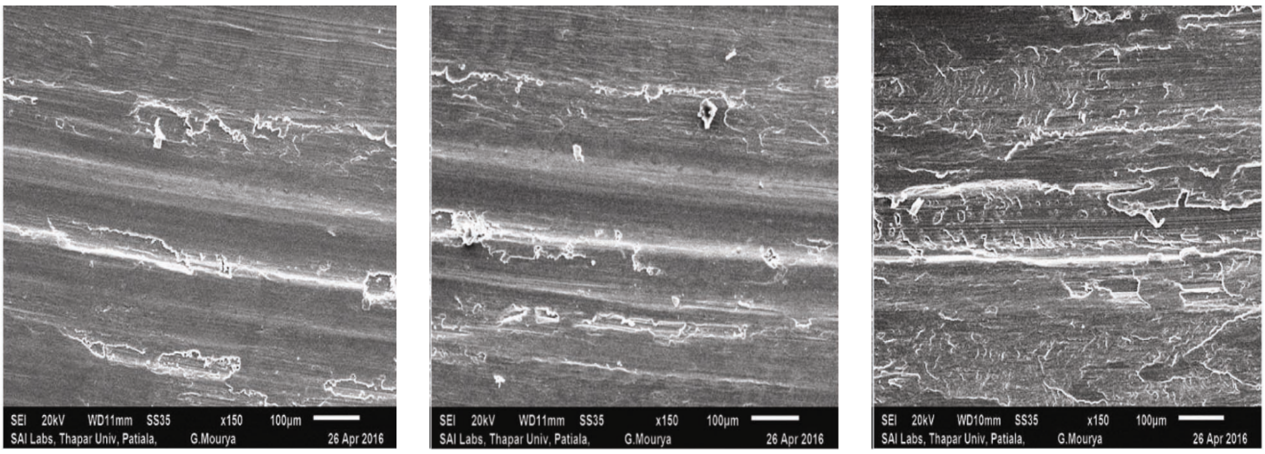
Table 8. Set of process parameters for confirmation tests.

Composite	Test no.	Reinforcement, (wt %)	Sliding speed (m/s)	Load (N)	Sliding distance (m)
AA6082-T6/SiC	1	7.12	1.6	30	800
	2	10.5	2.3	50	800
	3	12	2.4	30	1000
AA6082-T6/B_4C	1	5.5	2.4	60	800
	2	10	2.4	30	800
	3	15	2.25	30	1000



(a) (b) (c)

Fig. 15. Wear track of AA6082-T6/SiC composites used for confirmation tests: (a) Test 1; (b) test 2; (c) test 3.



(a) (b) (c)

Fig. 16. Wear track of AA6082-T6/B_4C composites used for confirmation tests: (a) Test 1; (b) test 2; (c) test 3.

AA6082-T6/SiC and AA6082-T6/B_4C composites, which are small enough to conclude that the present models and the dry sliding wear behaviour analysis here performed are accurate and can be used as predictive tools for wear applications.

4. Conclusions

The main conclusions obtained from the present work are as follows:

(1) AA6082-T6/SiC and AA6082-T6/B_4C composites were fabricated using stir casting technique and these composites wear behaviour analysis was successfully performed using Response surface methodology (RSM), resulting in two quadratic models.

(2) The addition of SiC and B_4C particulates led to an increase in these composites hardness, when compared to the

Table 9. Experimental and modelled results with error.

Composite	Test no.	Wear (g)		% Error
		Experimental results	Modelled results	
AA6082-T6/SiC	1	0.00561	0.00544	3.03
	2	0.00444	0.00417	6.08
	3	0.00424	0.00395	6.84
AA6082-T6/B_4C	1	0.00573	0.00557	2.79
	2	0.00308	0.00286	7.14
	3	0.00458	0.00432	5.67

un-reinforced AA6082-T6 alloy.

(3) Micro hardness of un-reinforced alloy comes out to be 101 HV. Addition of SiC increases the hardness from 101 HV to 113 HV at 20 % addition of reinforcement whereas addition of B_4C gives optimum hardness as 117 HV and that too at 15 % addition of reinforcement. Slight decrease in hardness has also been observed with 20 % addition of B_4C particulates.

(4) RSM analysis revealed that AA6082-T6/SiC and AA6082-T6/B_4C composites wear is decreased by increasing the reinforcement content and sliding speed. On the other hand, increases in load and sliding distance were found to lead to higher wear of these composites.

(5) The variables that presented the most significant effect on wear were sliding distance (with a contribution above 60 %), followed by sliding speed, load and finally reinforcement content, for both AA6082-T6/SiC and AA6082-T6/B_4C composites.

(6) Confirmation tests showed that the modelled results are very close to the experimental ones for both AA6082-T6/SiC and AA6082-T6/B_4C composites, thus validating the developed wear predictive models.

Acknowledgements

The authors wish to express their gratitude to the authorities of Mechanical Engineering Department, Thapar University - Patiala for providing the experimental facilities to conduct the work for this study.

References

[1] A. Meyveci, I. Karacan, U. Caligulu and H. Durmus, Pin-on-disc characterization of 2xxx and 6xxx aluminium alloys aged by precipitation age hardening, *Journal of Alloys and Compounds,* 491 (2010) 278-283.

[2] R. Abedinzadeh, S. M. Safavi and F. Karimzadeh, A comparative study on wear properties of nanostructured Al and Al/Al_2O_3 nanocomposite prepared by microwave-assisted hot press sintering and conventional hot pressing, *Journal of Mechanical Science and Technology,* 29 (9) (2015) 3685-3690.

[3] Y. Sahin and K. Ozdin, A model for the abrasive wear behaviour of aluminium based composites, *Materials and Design,* 29 (2008) 728-733.

[4] N. Natarajan, S. Vijayarangan and I. Rajendran, Wear behaviour of A356/25SiCp aluminium matrix composites sliding against automobile friction material, *Wear,* 261 (2006) 812-822.

[5] C. Nazik, N. Tarakcioglu and S. Ozkaya, Determination of effect of B_4C content on density and tensile strength of AA7075/ B_4C composite produced via powder technology, *International Journal of Materials, Mechanics and Manufacturing,* 4 (4) (2016) 251-261.

[6] J. K. M. Kwok and S. C. Lim, High speed tribological properties of some Al/SiC composites: I. Frictional and wear rate characteristics, *Compos. Sci. Technol.,* 59 (1999) 55-63.

[7] Y. Sahin, Wear behaviour of aluminium alloy and its composites reinforced by SiC particles using statistical analysis, *Materials and Design,* 24 (2003) 95-103.

[8] G. Miranda et al., Hybrid composites - Metallic and ceramic reinforcements influence on mechanical and wear behaviour, *Composites Part B: Engineering,* 74 (2015) 153-165.

[9] B. M. Girish et al., Optimization of wear behavior of magnesium alloy AZ91 hybrid composites using taguchi experimental design, *Metallurgical and Materials Transactions A,* 47A (2016) 3193-3200.

[10] R. N. Rao, S. Das and P. V. Krishna, Experimental investigation on the influence of SiC particulate reinforcement in aluminium alloy composites, *Proc. IMechEPart J: J. Engineering Tribology,* 220 (2008) 1-6.

[11] K. M. Shorowordi, A. S. M. A. Haseeb and J. P. Ceils, Velocity effect on wear, friction and tribochemistry of aluminum MMC sliding against phenolic brake pad, *Wear,* 256 (2004) 1176-1181.

[12] K. S. S. Raja and V. K. B Raja, Effect of boron carbide particle in wear characteristic of cast aluminium A356 composite, *Proceeding of National Conference on Contemporary Approaches in Mechanical Automobile and Building Sciences-2014, IOSR Journal of Mechanical and Civil Engineering* (2014) 73-77.

[13] S. Attar, M. Nagaral and H. N. Reddapp, Effect of B_4C particulates addition on wear properties of Al7025 alloy composites, *American Journal of Materials Science,* 5 (3C) (2015) 53-57.

[14] A. Baradeswaran and A. E. Perumal, Influence of B_4C on the tribological and mechanical properties of Al 7075-B_4C composites, *Composites: Part B,* 54 (2013) 146-152.

[15] A. Canakci and F. Arslan, Abrasive wear behaviour of B_4C particle reinforced Al2024 MMCs, *Int. J. Adv. Manuf. Technol.,* 63 (2012) 785-795.

[16] P. Sharma, S. Sharma and D. Khanduja, Parametric study of dry sliding wear behavior of hybrid metal matrix composite produced by a novel process, *Metallurgical and Materials Transactions A,* 46 (A) (2015) 3260-3270.

[17] S. V. Nair, J. K. Tien and R. C. Bates, SiC-reinforced aluminium metal matrix composites, *Int. Mater. Rev.,* 30 (6) (1985) 275-290.

[18] J. K. Chen and I. S. Huang, Thermal properties of aluminum-graphite composites by powder metallurgy, *Composites: Part B,* 44 (2013) 698-703.

[19] A. R. Kennedy, The microstructure and mechanical properties of Al-Si-B_4C metal matrix composites, *Journal of Materials Science,* 37 (2002) 317-323.

[20] S. Selvi and E. Rajasekar, Theoretical and experimental investigation of wear characteristics of aluminum based metal matrix composites using RSM, *Journal of Mechanical Science and Technology,* 29 (2) (2015) 785-792.

[21] S. Ghosh, P. Sahoo and G. Sutradhar, Wear behaviour of Al-SiCp metal matrix composites and optimization using taguchi method and grey relational analysis, *Journal of Minerals and Materials Characterization and Engineering,* 11 (2012) 1085-1094.

[22] N. Sharma, R. Khanna, G. Singh and V. Kumar, Fabrication of 6061 aluminium alloy reinforced with Si3n4/N-Gr and its wear performance optimization using integrated RSM-GA, *Particulate Science and Technology* (2016) Doi: 10.1080/02726351.2016.1196276.

[23] P. T. Arasu, R. Dhanasekaran and P. Kumar, Effect of hardness and microstructure on En 353 steel by heat treatment, *International Journal of Engineering and Science,* 2 (2013) 1-5.

[24] M. Singla, D. D. Dwivedi and L. Singh, Development of aluminium based silicon carbide particulate metal matrix composite, *Journal of Minerals & Materials Characterization & Engineering,* 8 (2009) 455-467.

[25] J. H. Ghazi, Production and properties of silicon carbide particles reinforced aluminium alloy composites, *International Journal of Mining, Metallurgy & Mechanical Engineering,* 1 (2013) 191-194.

[26] T. Raviteja, N. Radhika and R. Raghu, Fabrication and mechanical properties of stir cast Al-Si12Cu/B_4C composites, *International Journal of Research in Engineering and Technology,* 3 (2014) 343-346.

[27] R. O. Kuehl, *Design of experiments*, USA: Duxbury (2009).

[28] D. C. Montgomery, *Design and analysis of experiments*, New Delhi, Wiley India (P) Ltd. (2007).

[29] Y. Maz, S. C. Tjong and Y. Liang, High temperature creep behavior of nanometric Si_3N_4 particulate reinforced aluminium composite, *Materials Science & Engineering. A, Structural Materials : Properties, Microstructure and Processing,* 225 (1997) 125-134.

[30] E. T. Vazquez et al., Surface chemistry modification for elimination of hydrophilic Al_4C_3 in B4C/Al composites, *Materials and Design,* 89 (2016) 94-101.

[31] F. Ortega-Celaya, M. I. Pech-Canul and J. Lopez-Cuevas, Microstructure and impact behavior of Al/SiCp composites fabricated by pressureless infiltration with different types of SiCp, *Journal of Materials Processing Technology,* 183 (2007) 368-373.

[32] G. Arslan, F. Kara and S. Turan, Quantitative X-ray diffraction analysis of reactive infiltrated boron carbide-aluminium composites, *Journal of the European Ceramic Society,* 23 (2003) 1243-1255.

[33] J. C. Viala, J. Bouix and G. Gonzalez, Chemical reactivity of aluminium with boron carbide, *Journal of Materials Science,* 32 (1997) 4559-4573.

[34] Y. Sahin, Preparation and some properties of SiC particle reinforced aluminium alloy composites, *Materials and Design,* 24 (2003) 671-679.

[35] L. Poovazhagan et al., Characterization of hybrid silicon carbide and boron carbide nanoparticles-reinforced aluminum alloy composites, *Procedia Engineering,* 64 (2013) 681-689.

[36] K. Umanath, K. Palanikumar and S. T. Selvamani, Analysis of dry sliding wear behaviour of Al6061/SiC/Al_2O_3 hybrid metal matrix composites, *Composites: Part B,* 53 (2013) 159-168.

[37] D. Sanjeev, D. Siddhartha and D. Karabi, Abrasive wear of zircon sand and alumina reinforced Al-4.5 wt% Cu alloy matrix composites - A comparative study, *Composites Science and Technology,* 67 (2007) 746-751.

[38] M. A. Chowdhury, M. K. Khalil and D. M. Nuruzzaman, Effect of sliding speed and normal load on friction and wear property of aluminum, *International Journal of Mechanical & Mechatronics Engineering,* 11 (2011) 45-49.

[39] B. Bhushan and W. E. Jahsman, Propagation of weak waves in elastic- plastic and elastic-viscoplastic solids with interfaces, *Int. J. Solids and Struc*., 14 (1978) 39-51.

[40] B. Bhushan and W. E. Jahsman, Measurement of dynamic material behavior under nearly uniaxial strain condition, *Int. J. Solids and Struc*., 14 (1978) 739-753.

Gurpreet Singh is currently a Ph.D. Research Scholar at YMCA University of Science and Technology, A State Govt. University, India. He obtained his B.Tech. from Kurukshetra University in 2006 and M.E. degrees from PEC University of Technology in 2010. His current research is mainly focused on the study of mechanical behaviour; tribological characteristics and wear resistance of metal matrix composites particularly for aluminum based hybrid composites.