

Dry sliding wear behavior of mono (Al2219/B₄C) and hybrid (Al2219/B₄C/Gr) metal matrix composites by using statistical technique

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Abstract: Stir casting was used to make aluminium metal matrix composites (AMMCs) reinforced with boron carbide (B₄C) and graphite (Gr) particles in this work. On a pin-on-disc device, dry sliding wear behaviour of created composites was investigated using a variety of sliding distances, loads, and speeds. Taguchi method was employed to optimize the information in a managed way. Analysis of variance was employed to look at the put on behavior of base alloy (Al2219), mono (Al/B₄C) and hybrid (Al/B₄C/Gr) metallic matrix composites. The correlations have been mounted by means of linear regression models and validated the usage of affirmation tests. The obtained results indicated that B₄C content, sliding distance is incredibly affected by the dry sliding wear accompanied by sliding speed and utilized load. The incorporation of B₄C and Gr particles in aluminium improves the tribological characteristics. The SEM images of mono composite shows the deep grooves on worn surface. It demonstrates the signs of abrasive wear of mono composite. The hybrid composite exhibits excellent wear resistance when compared to mono composite and base alloy. The main reason of that is the Gr particles act as a solid lubricating material in the hybrid composite (Al/B₄C/Gr).

Keywords: stir casting, Al2219 alloy, mono composite, hybrid composites, wear behaviour, statistical technique

1 Introduction

Aluminium metal matrix composites (AMCs) are materials which possess hard reinforcement with the ceramic particles having soft matrix produce

composite materials. These materials produce greater strength, light weight and high performance when compared to monolithic materials. It can be tailorable to precise applications due to their properties like stiffness and specific strength. Aluminium metal matrix composites are advanced materials for several applications like, aviation, automobile, defense and other engineering sectors. Superior wear and seizure resistance of metal matrix materials (MMCs) used in tribological applications such as brake drums, piston rings, cylinder blocks and liners, and most of the reinforcing ceramic particles are boron carbide (B₄C), titanium diboride (TiB₂), alumina (Al₂O₃), silicon carbide (SiC) particles and so on. Composite materials possess variable strengthening mechanisms when compared to other conventional materials. As composite materials have hard reinforcing particles enhances the mechanical properties such as tensile strength, high hardness of the material and by this the wear resisting property is also increases [1–5].

Aluminium metal matrix composites (AMCs) are fabricated by various methods such as, squeeze casting, liquid infiltration, stir casting, spray deposition and other advanced powder metallurgy methods. Among different fabrication techniques, conventional stir casting is simple, economical and attractive methods for producing AMCs. Recent research on homogenous mixing achieved by selecting process parameters like molten metal temperature, uniform feed of the particles, stirring speed and processing time [1, 2].

The B₄C particles are very hard, high stiffness, low thermal conductivity and these ceramic particles reinforcing with metal matrix are widely used in armour tanks, engine sabotage powders, nozzles and numerous industrial applications. Gr particles were added as a secondary rein-

forcing element as a natural solid lubricant, which finds wide applications in tribology. Gr reinforced composites exhibit low wear rate, low density and excellent anti seizing properties [3, 4].

Auradi *et al.* [3] reported that the mechanical properties of composites depend upon size, shape and volume fraction of particles. They reported that Gr used as a secondary reinforcement material having low density of 2.25g/cc, hardness of 1-2 Mohr scale and melting temperature of 3650°C which is widely used in tribological application such as automobile, journal bearings because of its solid lubricating property. It improves the seizure resistance feature in Al exhibiting lower friction coefficient and high hardness [4].

Various investigations have been carried out on reinforcement particles of Al₂O₃, SiC, TiB₂ with matrix of aluminium alloy. Basavarajappa *et al.* [5] reported that Gr particles as a secondary reinforcing element present in hybrid composite increases the wear resisting property of the material. The formation of protective shielding between pin and disc face due to the smearing of Gr particles reduces the wear of the material. Sliding distance has highest physical and statistically influence on the wear composite followed by load and sliding speed. Gangadhar *et al.* [6] reports a paper on aluminium metal matrix composites containing red mud particles improves the strength, wear behavior and hardness of the composite. It is mainly due to the presence of red mud content in the matrix material. And also they reported that increase in red mud particles gives maximum wear resistance to the composite and decrease the specific wear rate. Elango *et al.* [7] studied the wear performance of hybrid metal matrix composites (LM25/SiCp/TiO₂) using dry sliding wear test. The results reveal that wear rate increases with increase in sliding distance and load conditions and decreases with increasing in volume content of the reinforcement. The friction coefficient decreases with the increase in load and SiC and TiO₂ particle reinforcement.

Hemanth *et al.* [8] carried an investigation on mechanical properties and wear behaviours of kaolinite (Al₂SiO₅) and carbon(C) particles reinforced chilled metal matrix composites (CMMCs) by experimental method and compared with finite element (FE) simulation method. They found that the cryogenic chilled MMCs with Al₂SiO₅-9% and C-3% reinforced content provides high strength, hardness and high wear resistance. The obtained result indicates good agreement between experimental values and simulated (FE) values. Wear resistance of the composites improves as the dispersed content increases. Scanning Electron Microscope (SEM) result reveals that at lower load condition shows the light grooves formation on the wear

surface and higher loads, large plastic deformation and localize melt. Singh *et al.* [9] reported that load, sliding speed and interaction of sliding speed and load were more significant on wear rate of composites. The experimental values shows good agreement with the models analysed. The coefficient of friction is directly proportional to sliding speed and applied load. Regression modelling for wear rate composites reveals that inversely proportional to sliding speed and distance and directly proportional to load applied.

Gaitonde *et al.* [10] reports a paper on wear and corrosion properties of Al-5083 reinforced with Al₂O₃ and Gr hybrid composites. Experimental results on Al₂O₃ and Gr in Al-5083 reveal that prepared hybrid composite shows the improvement in hardness, reduces wear and corrosion rate. Observations reveal that wear rate of the composite material increases with increase in time duration, impact velocity and sand concentration because of the protective layer formed against the impact of slurry. And also they observed that the increase in hardness of the composite by increase in percentage of reinforcements. Satish *et al.* [11] investigated the tribological wear behavior of aluminium (LM30) matrix alloy with pure ceramic particles like, SiC, B₄C and Gr using dry sliding test. The analysis results show that wear rate decreases with increases of SiC and B₄C reinforcement percentage in the composites. Xavier *et al.* [12] studied the dry sliding wear behavior of Al-MMC reinforced with wet grinder stone dust particles an industrial waste. They observed that the wear rate of MMC reinforced with 20% grinder stone dust particles indicates high hardness and wear resistance when compared to base alloy. It is mainly due to hard ceramic particles in composites. Wear rate increase with increase in sliding speed, load and distance. SEM wear studies on worn surface of MMC shows the thick and brittle oxide layer. It was formed at higher load and speed conditions.

Some of the researchers studied the tribological and mechanical properties with solid lubricants as a secondary reinforcement. They found that the solid lubricants acts as self-lubrication and have good properties like low density, shock resistance, good machinability and formability [13–16]. Hence, it can be chosen as secondary reinforcement for the metal matrix hybrid composites. Kumar *et al.* [14] studied the wear behavior of hybrid metal matrix composites (Al2219/n-B₄C/MoS₂) using dry sliding wear test. The test results on n-B₄C and MoS₂ as a secondary reinforcement in Al-2219 matrix indicates the high wear resistance and high hardness when compared to mono composite (Al2219/n-B₄C). Chandra and Chandrasekhar [15] reported the wear behavior of hybrid metal composite with boron nitride (BN) as a secondary reinforcement. They found that

Table 1: The chemical composition of Al2219 alloy in percentage by weight

Fe	Mn	Zn	Ti	Si	Mg	V	Zr	Cu	Al
0.3	0.3	0.005	0.05	0.2	0.02	0.1	0.18	6.3	Balance

the addition of B₄C and BN reinforcement in Al6061 alloy improves the wear resistance of the composite.

Şimşek [16] studied the effect of B₄C and Gr reinforcements on wear behaviours of Al-Graphite/B₄C hybrid composite. The results indicated that Gr reinforcement was significant contribution to the wear resistance of the hybrid composite. Miloradovic *et al.* [17] studied the wear characteristics of ZA27/%SiC and ZA27/%SiC/%Gr hybrid composites. They observed that the hybrid composite (ZA27/%SiC/%Gr) was higher wear resistance when compared to mono composite (ZA27/%SiC). It is mainly due to the solid lubrication obtained by the existence of Gr film on the contact surface of the hybrid composite.

The above literature review provides the scope for the new researchers to investigate the wear behavior of metal matrix composites with different weight percentage of ceramic particles reinforcement under different load, sliding distance and speed conditions. The main aim of the present work is to study the effect of individual (mono composite: Al/B₄C) and collective (hybrid composite: Al/B₄C/Gr) reinforcement of the base alloy (Al2219) in a dry sliding wear test condition, in comparison to the base alloy. It is envisioned to find the optimum level of operating parameters to minimize the material loss under test conditions. The study provides detailed investigation on effect of various parameters like sliding speed, sliding distance and load and their interactions using statistical technique and compared the experimental results with optimized values. Surface examinations of wear test specimens have been analysed through SEM and XRD analysis.

2 Experimental procedures

2.1 Materials and method

The Al2219 matrix material was chosen because of excellent properties such as high strength, high fracture toughness, resistant to corrosion cracking and damage tolerance at cryogenic and elevated temperatures. It is widely used in automobiles, space shuttles, supersonic aircraft outer skin and other structures members. A detail of the chemical composition of Al2219 is given in Table 1. B₄C of average 90 micron size of particles and secondary reinforcement element Gr of 30 micron size were used as reinforcement ma-

terials. Two types of composites were prepared; one with mono composite (Al2219 + 8% B₄C) and second one with hybrid composite (Al2219+8% B₄C+3%Gr) were compared with pure base alloy of Al2219. Both mono and hybrid composites were prepared using two step stir casting method by means of resistance furnace connected with stain less steel stirrer and it is adopted to prevent agglomeration and clustering of particles. Matrix alloy (Al2219) was taken in a graphite crucible and heated to above melting temperature and gradually decreased below liquid temperature (semi-solid state). Pre-heated B₄C and Gr particles were added into the molten matrix alloy. Super-heated composite slurry was poured in to the mould of 12 mm diameter and 100 mm length pre-heated die.

Finally, the specimens were cleaned and pre-machined with CNC turning machine. For the microstructure study, specimens were cut by CNC electric discharge machining (wire EDM) with different cross-section area and polished with different grade emery papers as per metallographic procedure. Uniform distribution of particles in matrix was confirmed through optical micrographs and X-ray diffraction (XRD) analysis.

2.2 Microstructural study

The optical microstructure for base alloy (Al2219), mono composite (Al2219+8% B₄C) and hybrid composite (Al2219+8% B₄C+3% Gr) are as shown in Figure 1. For the mono composite shows that uniform distribution of B₄C particles in the Al2219 matrix material (Figure 1(b)). This is mainly due to proper stirring method used during processing. By addition of halide salt (K₂TiF₆) along with the reinforcement particles gives good wettability between Al and B₄C. Use of halide salt (K₂TiF₆) during casting has wettability and bonding between Al and B₄C and also uniform dispersion of reinforcing B₄C particles in Al matrix material. K and F present in K₂TiF₆ contribute for removal of oxide on the Al surface. The reason is that the halide salt processed with B₄C particles and produces Ti compound surround the B₄C particle surface. These B₄C particles continuous layers of Ti confirm the products of TiC and TiB₂. Similar results were reported by Alidokht *et al.* [18], and G. Ranganath *et al.* [19]. In hybrid composites fairly uniform distribution of small black particles of Gr can observed

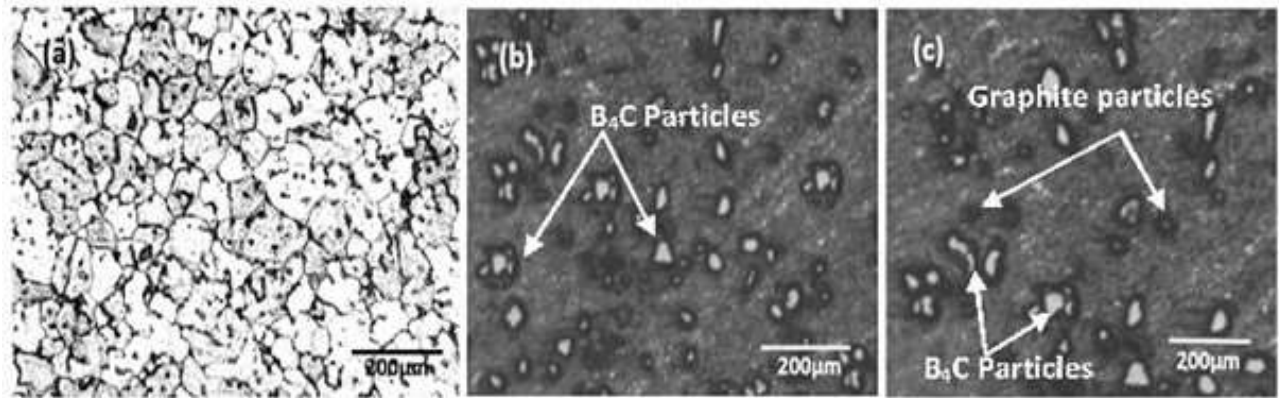


Figure 1: (a) Microstructure of base alloy (Al2219); (b) mono composite (Al2219+8%B₄C); (c) hybrid composite (Al2219+8% B₄C+3%Gr)

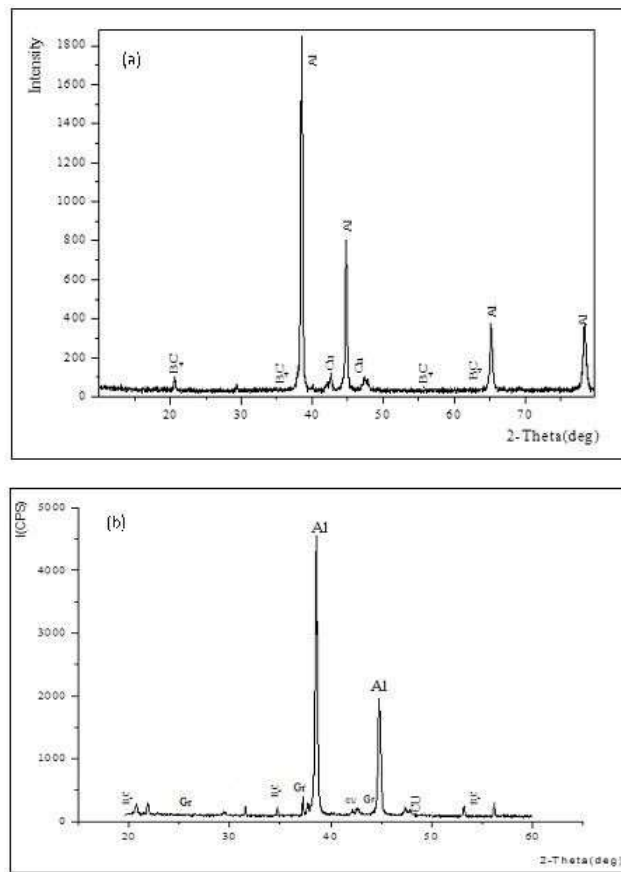


Figure 2: XRD profiles of (a) mono composite (Al2219+8% B₄C); (b) hybrid composite (Al2219+8% B₄C+3% Gr)

along with B₄C particles in Al matrix material as seen in Figure 1(c). The confirmation of B₄C and Gr particles in the base matrix through X-ray diffraction (XRD) analysis. From Figure 2(a) Peaks of Al, B₄C and copper are observed from the XRD pattern and this confirms the presence of B₄C in Al2219 alloy and From Figure 2(b) Peaks of Al, B₄C,

Gr and Copper are observed from the XRD pattern and also this confirms the presence of B₄C and Gr in Al2219 alloy.

2.3 Planning of experiments

Taguchi's technique is a robust design technique, generally aimed to produce high quality product to the manufacturer at economical and widely used for engineering applications. It is developed to investigate the influences of various parameters with mean and variance of a process performance characteristic to define the functioning of process. In the present work, dry sliding wear tests were

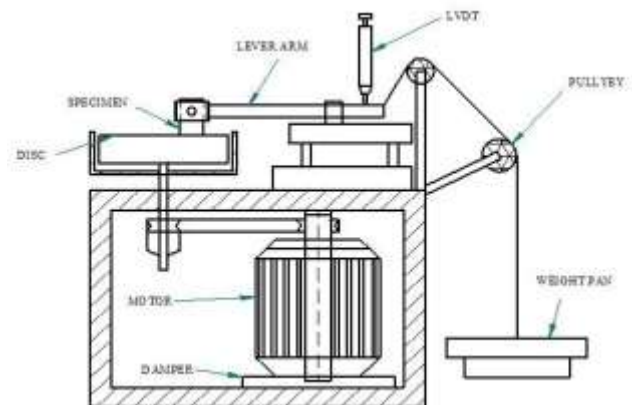


Figure 3: Schematic diagram of wear test apparatus

Table 2: Process parameters fixed with their levels

Level	Sliding speed (m/s)	Load (N)	Sliding distance (m)
1	1	19.6	1.53
2	3.06	19.6	1500
3	4.59	29.43	1500

Table 3: Orthogonal array of Taguchi wear test results

Test	Sliding speed (S), m/s	Applied load (L), N	Sliding distance (D), m	Wear rate Al2219 (mm ³ /m) (10 ⁻³)	Wear rate 8% B ₄ C (mm ³ /m) (10 ⁻³)	Wear rate 8% B ₄ C + 3% Gr (mm ³ /m) (10 ⁻³)
1	1.53	9.81	500	0.82	0.38	0.31
2	1.53	9.81	1000	1.81	0.92	0.84
3	1.53	9.81	1500	2.21	1.31	1.32
4	1.53	19.6	500	1.81	0.93	0.94
5	1.53	19.6	1000	2.39	1.49	1.51
6	1.53	19.6	1500	3.21	2.32	2.32
7	1.53	39.2	500	1.75	0.85	0.92
8	1.53	39.2	1000	3.02	2.21	1.54
9	1.53	39.2	1500	4.02	3.2	2.91
10	3.06	9.81	500	1.52	0.72	0.51
11	3.06	9.81	1000	2.09	1.29	0.91
12	3.06	9.81	1500	2.68	1.88	1.52
13	3.06	19.6	500	1.76	0.96	0.81
14	3.06	19.6	1000	2.42	1.61	1.38
15	3.06	19.6	1500	2.81	2.02	1.71
16	3.06	39.2	500	2.11	1.32	0.91
17	3.06	39.2	1000	2.92	2.12	1.72
18	3.06	39.2	1500	3.32	2.52	2.11
19	3.06	9.81	500	1.27	0.67	0.71
20	4.59	9.81	1000	1.82	1.22	1.12
21	4.59	9.81	1500	2.71	2.11	2.16
22	4.59	19.6	500	2.02	1.42	1.44
23	4.59	19.6	1000	3.01	2.41	2.50
24	4.59	19.6	1500	3.96	3.36	3.52
25	4.59	39.2	500	1.83	1.23	1.21
26	4.59	39.2	1000	2.83	2.23	2.12
27	4.59	39.2	1500	4.46	3.86	3.41

performed using pin and disc apparatus and experimental trials are applying using Taguchi L₂₇ orthogonal array. The schematic diagram of wear test machine is as in Figure 3. The wear test specimens size of height 30 mm diameter 10 mm and were prepared as per ASTM standards G99-95 using CNC turning machine. Test specimen pressed against the rotating AISI D2 steel disc of 65 HRC by applying load. Experiment was conducted by measuring the initial and final weight with the accuracy of 0.001g. Trial runs were performed to find upper and lower limits for the identified process parameters such as sliding speed (S), applied load (L) and sliding distance (D) were assigned is as in Table 2 and experimental layout plan of 27 trials and the output response of wear rate for the base alloy (Al2219), mono composite (Al2219 + 8% B₄C) and hybrid composite (Al2219+8% B₄C+3% Gr) are showed in Table 3.

3 Results and discussion

The main objective is to study the influence of sliding distance (D), sliding speed (S) and applied load (L) on the dry sliding wear behavior of base alloy, mono composite and hybrid composite materials. The test parameters and their levels selected for the experiments were based on Taguchi standard (L₂₇) orthogonal array and it was employed to acquire the data in a controlled way. The influence of sliding distance, sliding speed and applied load on wear rate of base alloy, mono and hybrid composites were analysed by analysis of variance (ANOVA). The wear rate analysis is carried out using smaller is the better criterion and same response. The ANOVA results are shown in Table 4, 5 and 6. Analysis was carried out at a confidence level of 95%. The

Table 4: ANOVA analysis of Al2219 alloy

Source	Seq SS	Dof.	Adj MS	F	P	% C
S	0.5311	2	0.26554	7.23	0.016	2.76
L	5.0164	2	2.50821	68.33	0.000	26.07
D	11.6179	2	5.80893	158.26	0.000	60.39
S*L	0.6960	4	0.17399	4.74	0.030	3.61
S*D	0.6585	4	0.16463	4.49	0.034	3.40
L*D	0.4238	4	0.10594	2.89	0.094	2.20
Residual error	0.2936	8	0.03671			1.52
Total	19.2375	26				100

R-Sq=98.5%, R-Sq (Adj)=95.0%

Table 5: ANOVA analysis of mono-composite (Al2219+8% B4C)

Source	Seq SS	Dof.	Adj MS	F	P	% C
S	1.5746	2	18.25	18.25	0.01	8.04
L	4.6847	2	2.34236	54.31	0.000	23.94
D	11.0607	2	5.53036	128.22	0.000	56.51
S*L	0.6498	4	0.16244	3.77	0.052	3.31
S*D	0.6331	4	0.15828	3.67	0.056	3.23
L*D	0.6249	4	0.15623	3.62	0.057	3.19
Residual error	0.3451	8	0.04313			1.78
Total	19.5729	26				100

R-Sq=98.5%, R-Sq (Adj)=95.0%

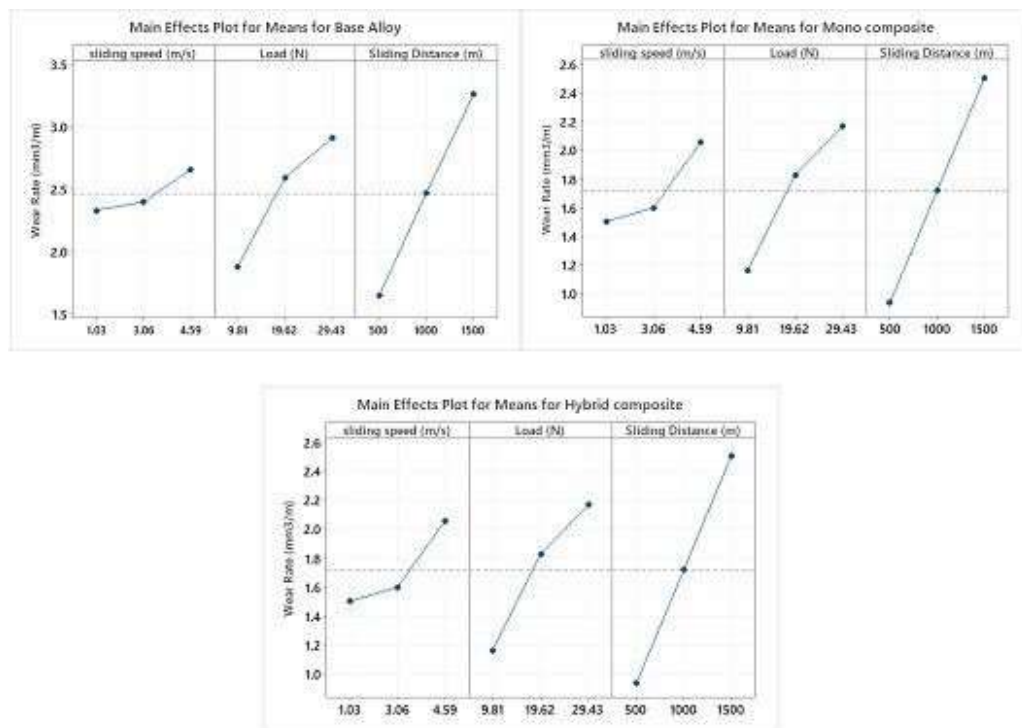


Figure 4: Main effects plots for wear rate of (a) base alloy; (b) mono composite; (c) hybrid composite material

Table 6: ANOVA analysis of hybrid composite (Al2219+8% B4C + 3% Gr)

Source	Seq SS	Dof.	Adj MS	F	P	% C
S	2.8017	2	1.40085	49.15	0.000	15.51
L	3.7598	2	1.87988	65.95	0.000	20.82
D	9.6880	2	4.84401	169.94	169.94	53.64
S*L	0.5865	4	0.14663	5.14	0.024	3.24
S*D	0.6510	4	0.16276	5.71	0.018	3.36
L*D	0.3432	4	0.08581	3.01	0.086	1.90
Residual error	0.2280	8	0.02850			1.26
Total	18.0582	26				100.00

R-Sq=98.7%, R-Sq (Adj)=95.9%

consequence of the factors was confirmed by the main effects plots (Figure 4).

3.1 ANOVA analysis results

Table 4 shows the ANOVA analysis results for wear behavior of Al2219 alloy. It indicates that the sliding distance (60.39%), applied load (26.07%) and sliding speed (2.76%) have greater influence on wear rate. Similarly, In case of mono composite (Al2219+8% B4C), the sliding distance (56.51%), applied load (23.94%) and sliding speed (8.04%) has great influence on wear rate (Table 5). Whereas for hybrid composite (Al2219+8% B4C+3% Gr), sliding distance (53.64%), applied load (20.82%) and sliding speed (15.51%) have influences on wear rate (Table 6). However, the interactions between the all three composite factors were minimum. It can be revealed that the sliding distance is most significant followed by and applied load and sliding speed on wear rate in all the composites. However, the influence of graphite particle in hybrid composite increase in wear resistance when compared to mono composite and base alloy materials. Furthermore, in hybrid composites (Al2219+8% B4C+3% Gr) wear resistance is more than base alloy (Al2219) and mono composite (Al2219+8% B4C) because of solid lubricant property. Graphite acts as a self-lubricating material, for that wear rate initially controlled. The coefficient of friction between pin and disc is less in hybrid composite. The reason is that the Graphite particles acts as a lubricating material in hybrid composite and resistance to wear and also friction between pin and disc is reduced. For longer sliding distance there is a tendency of an increase in subsurface micro cracking and severe fracturing of B4C particles. The fractured B4C particles cause further scrabbling on the composites and formation of mechanically mixed layer. This causes weakened tribo-layer formation on the surface of hybrid composite

material. Similar results were found in Basavarajappa *et al.* [5] and S. P. Dwivedi, G. Dwivedi [20].

The main effects plots for mean for the wear rate of base alloy, mono and hybrid composites are shown in Figures 4 (a), (b) and (c), respectively. The Figure 4 shows main effects plots for the base alloy, mono composite and hybrid composite material, the increase in sliding speed, applied load and sliding distance with increases in wear rate. It indicates that the wear rate increases with linear increases in sliding distance. The main reason is that the increase in temperature and softening of the surface and subsurface of the wear surface. Further, the wear rate increases with increase in applied load and sliding speed. It is observed that at 20 N load and sliding speed of 3m/s wear rate is an almost same. It is due to stable oxide layer formation on the matrix surface. At loads in between 20 N to 40 N the temperature rises causes some of the oxide layer to fracture resulting in more wear. In Al2219 alloy there is no matrix strengthening particles, thus the material softening effect is more increased in sliding distance as observed in Figure 4(a).

In case of mono composite, the reinforcement of hard B4C particles improvement in wear rate. As the sliding speed increases wear rate is also increases due to high strain rate sub surface deformation this leads to delamination for enhancement of wear rate. The wear rate of composites was much lower when compared to pure base alloy. The hybrid composite has less wear rate while compared to mono and pure base alloy. In Al2219 alloy subsurface plastic deformation begins at or below 20 N load. When wear rate is low, the applied load also is low and it increases wear with increase in applied load. For Al2219 alloy wear rate increases rapidly above 20 N load and form severe wear regime. As the load increases delamination wear also increases. The wear surface of base alloy at higher load of 40 N shows the serrated surface layer. Surface observed to be rough with flow lines and deep grooves

indicates the strong delamination found in pure base alloy. In mono composite containing hard reinforcing B₄C particles increase the hardness of the material. Increase in hardness attributed improvement in wear rate and seizure resistance of materials. The presence of hard B₄C particles increases the strength of the composite hence applied load is insufficient to cause strain gradient to initiate plastic flow. These hard particles reduce the inter particle spacing and act as a strong barrier for dislocation motion.

In hybrid composite containing graphite particles decreases the wear rate due to solid lubricating property of graphite. The Gr particles smeared from contact surface during sliding surface and forms mixed layer which avoids metal to metal contact. At higher loads accelerates the abrasive wear due to more local stress forming deeper grooves. There is a thermal mismatch between particle and base material generates the dislocation density which enhances contact load by work hardening effect. As the load increases dislocation move past the particles pileup dislocation at the grain boundary and stress concentration initiates the delamination crack at the particle or matrix material due to shear deformation at the sub surface. In hybrid composites material wear rate is less due to formation of tribo-layer in between sliding surfaces. This layer reduces micro cutting/scratching especially at higher loads.

The wear rate increases with increase in sliding distance for all the composites. However for hybrid composites less wear rate is observed compare to mono and Al2219 alloy. In case of Al2219 there is no strengthening mechanism and ductile in nature hence wear rate increases. At initial stage of sliding distance there is not much change in wear loss for all the types of composite. The incorporation of B₄C particles in Al2219 alloy improves the wear resistance as compared to base alloy. In the beginning stage of sliding the asperities of the pin and the counter face of the disc were in contact with each other. As the sliding distance increases further B₄C particles which are held to the pin are subjected to less wear when compared to base alloy. The reason is that the hard ceramic particles are able to resist wear for longer time and increases the property of brittleness of the material and wear rate decreases.

On the basis of analysis of variance (ANOVA) further the responses are calculated, the response for mean are calculated and on basis of it the rank are allotted according to the mean value as shown in Tables 7, 8 and 9. It is clear among the process parameters that the sliding distance (Rank-1) is most significant factor followed by applied load (Rank-2) and sliding speed (Rank-3) for all the materials.

The comparison of wear rate of base alloy, mono composite and hybrid composite materials is as in Figure 5. The obtained results shows that the wear rate of base alloy and

Table 7: Response table for means for base alloy (Al2219)

Level	Sliding speed (S)	Load (L)	Sliding Distance (d)
1	2.331	1.881	1.653
2	2.399	2.593	2.473
3	2.657	2.912	3.260
Delta	0.326	1.031	1.607
Rank	3	2	1

Table 8: Response table for means for mono composite (Al2219+8% B₄C)

Level	Sliding speed	load	Sliding distance
1	1.5033	1.1644	0.9367
2	1.5989	1.8267	1.7178
3	2.0567	2.1678	2.5044
Delta	0.5533	1.0033	1.5678
Rank	3	2	1

Table 9: Response table for means hybrid composite (Al2219+8% B₄C+3%Gr)

Level	Sliding speed (S)	Load (L)	Sliding distance (d)
1	1.3922	1.0344	0.8544
2	1.2778	1.7856	1.5078
3	2.0111	1.8611	2.3189
Delta	0.7333	0.8267	1.4644
Rank	3	2	1

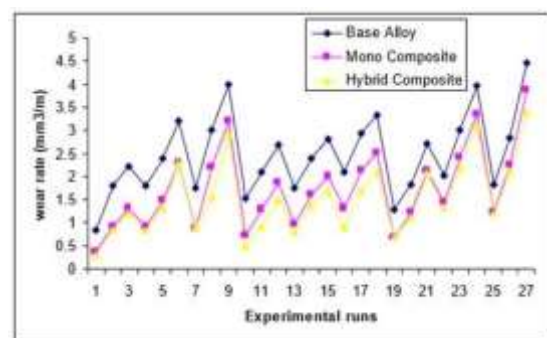


Figure 5: Comparison of experimental results for base alloy (Al2219), mono composite (Al2219+8% B₄C) and hybrid composite (Al2219+8% B₄C+3%Gr) materials

mono composite are higher than hybrid composite. It indicates that graphite (Gr) is considered as one promising filler material and as secondary reinforcement in metal matrix composites.

3.2 Linear regression models

A linear regression analysis attempts to model the relationship between two or more predictor variables and response variable by fitting a linear equation to the observed data. To establish the correlation between the wear parameters such as sliding speed (S), load (L) and sliding distance (D) and wear rate, the linear regression models was used. The regression equation for base alloy (Al2219), mono (Al2219+8%B₄C) and hybrid Al2219+8%B₄C+3%Gr composites are given in Eq. (1), (2) and (3), respectively.

$$\begin{aligned} \text{Wear rate of base alloy} = & -0.211 + 0.106(S) \quad (1) \\ & + 0.0324(L) + 0.00161(D) + 0.00012(S*L) \\ & + 0.00003S*D) + 0.000025(L*D) \end{aligned}$$

$$\begin{aligned} \text{Wear rate of mono composite} = & -1.13 + 0.181(S) \quad (2) \\ & + 0.0317(L) + 0.00157(D) + 0.0001251(S*L) \\ & + 0.000028(S*D) + 0.000022(L*D) \end{aligned}$$

$$\begin{aligned} \text{Wear rate of hybrid composite} = & -1.09 \quad (3) \\ & + 0.202(S) + 0.0247(L) + 0.00146(D) + 0.000118(S*L) \\ & + 0.0000246S*D) + 0.0000221(L*D) \end{aligned}$$

3.3 Confirmation test

Confirmation tests were conducted according to the optimized values (Table 7, 8 and 9) and Main effects plots (Figure 4) are shown in Table 10. The experiments were conducted and compared with optimized values are shown in Table 11. It is observed that the calculated error is less than 8% for wear rate of all the materials. Hence, obtained results confirms the reasonable degree of approximation.

4 Microstructural analysis of wear surface

Figure 6 shows the SEM images of the worn surfaces of base alloy (Al2219), mono composite (Al2219+8% B₄C) and hybrid composite (Al2219+8% B₄C+3% Gr) materials tested at 20 N load and sliding distance of 1000 m and sliding speed 3 m/s. For the base alloy (Al2219) worn surface morphology of the specimen is as shown in Figure 6(a). The image shows that softening of the Al2219 at interface temperature and forms severe plastic deformation. And also observed the high strain rate subsurface deformation and delamination. For mono composites (Al2219+8% B₄C) consists of B₄C particles improves the wear resistance when comparison to unreinforced alloy. At lesser load grooves are formed shallow and less material removable is observed (Figure 6(b)). These asperities are plastically deformed from the contact surface. There is a possibility of fracturing of small particles leading to fine debris. These plastically deformed surface forms the valley of the material between pin and disc. During further action there is a possibility of fracturing a few asperities and forms a very fine debris the sliding distance increases the wear rate also increases due to more time in contact with the surface. Similar results were found in other researchers [15, 16]. In the hybrid composite (Al2219+8% B₄C+3% Gr) formation of tribo-layer in between contact surfaces. Along with protective layer graphite smears out and minimize wear loss of the composite at selected parameters. The asperities between specimen and counter face formed under the influence of applied load. In the beginning, specimen and counter face are allied to fill the valley of the matrix material. During the course of action, fracturing a few asperities

Table 10: Confirmation test parameters for wear rate of Al2219, mono and hybrid composites

Exp. No.	S (m/s)	L (N)	D (m)	Composition
1	2.29	14.71	750	Base alloy(Al2219)
2	3.82	24.5	1250	Mono composite (Al2219+8%B ₄ C)
3	5.35	44.1	2000	Hybrid composite(Al2219+8%B ₄ C+3%Gr)

Table 11: Confirmation test results of experimental values along with regression values

Exp. No.	Wear Rate (mm ³ /m)			Average Exp.	Reg. Model	Error %
	Replicate 1 (Exp.)	Replicate 2 (Exp.)	Replicate 3 (Exp.)			
1	1.99×10 ⁻³	1.05×10 ⁻³	1.65×10 ⁻³	1.55 ×10 ⁻³	1.50 ×10 ⁻³	4.69
2	2.53×10 ⁻⁶	2.62×10 ⁻⁶	2.04×10 ⁻⁶	2.38×10 ⁻⁶	2.31 ×10 ⁻⁶	3.75
3	4.22×10 ⁻⁶	3.99×10 ⁻⁶	4.39×10 ⁻⁶	4.20×10 ⁻⁶	3.98 ×10 ⁻⁶	4.78

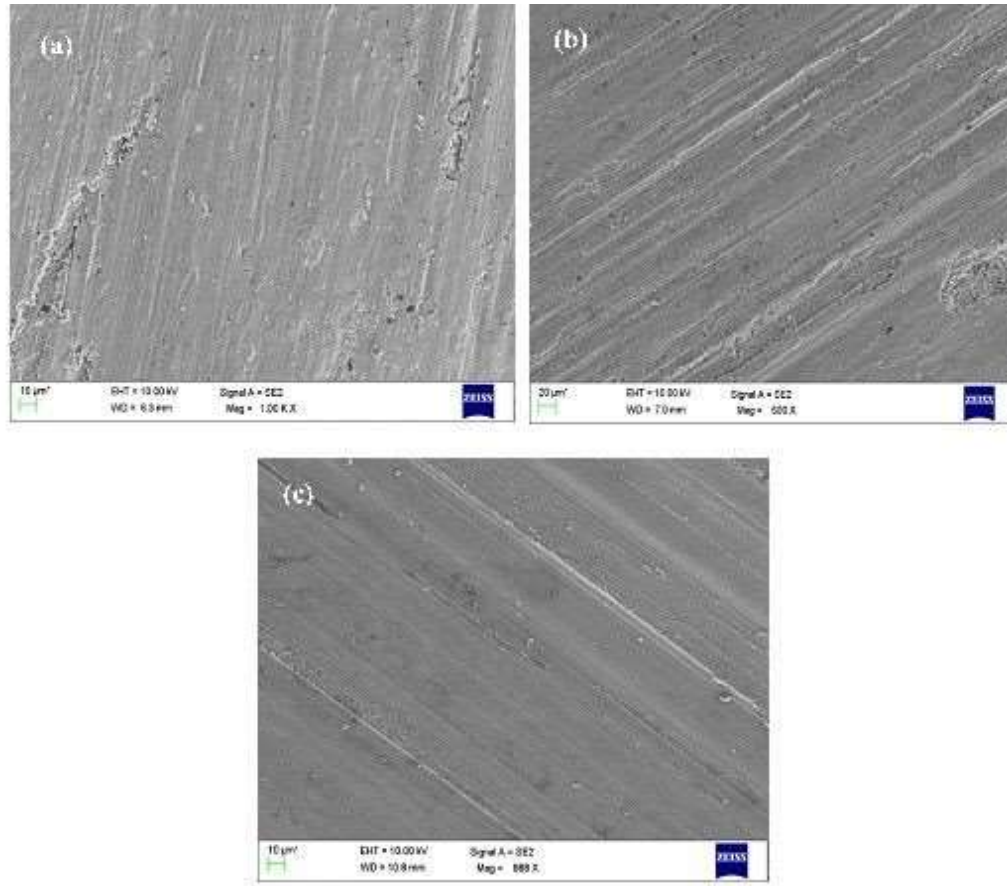


Figure 6: Typical wear surface at applied load of 19.6 N and sliding speed of 3.06 m/s and sliding distance of 1000 m (a) base alloy; (b) mono composite; (c) hybrid composite.

on matrix surfaces route a very fine debris. The presence of Gr forms a protective mechanically mixed layer (MML) between pin and the counter face (Figure 6(c)).

Figure 7 shows the SEM images of the worn surface of base alloy, mono composite and hybrid composite materials tested at applied load of 39.2 N, sliding distance of 1500 m and sliding speed 4.59 m/s. For the base alloy (Al2219) worn surface morphology of the specimen is as shown in Figure 7(a). At higher load and sliding speed, adhesive wear mechanism was observed in base alloy. It shows that the unreinforced matrix experiencing wide plastic deformation. It is due to its ductility and slider enters deeply into the soft matrix. Hence more material losses observed in wear surface. Figure 7(b) shows the worn surface of mono composite (Al2219+8% B4C) material with large number of deep abrasive grooves presence along the sliding direction. It is mainly because of high pressure and temperature, hard B4C particles abrading on the surface and forming of deeper grooves and protect base matrix loss during the material wear test. Figure 7(c) shows SEM images of the hybrid composite (Al2219+8% B4C+3%

Gr) material. In Al2219+8% B4C+3% Gr composites wear resistance increases with creation of lubricating layer as graphite particles smears out from the surface. Hence, lean and narrow grooves of less depth are formed on the wear surface. The reason is that at the increasing sliding distance, abrasive wear causes troughs and straight grooves along the sliding direction. Later stage, formation of gathered laminate layers occurs. It is due to increase of plastic deformation and high wear causes destruction of the surface in depth and some indigenous departure of the matrix material occurs. It can be revealed that addition of B4C reinforcement has been found to reduce the wear rate in mono composite when compared to base alloy. In case of hybrid metal matrix composites, presence of B4C and Gr particles reinforcement increases the wear resistance and volume loss of the material and also establishment of protective layer between specimen and counter face. The can be concluded that graphite (Gr) particles can be considered as one of the promising filler materials and as secondary reinforcement in hybrid metal matrix composites.

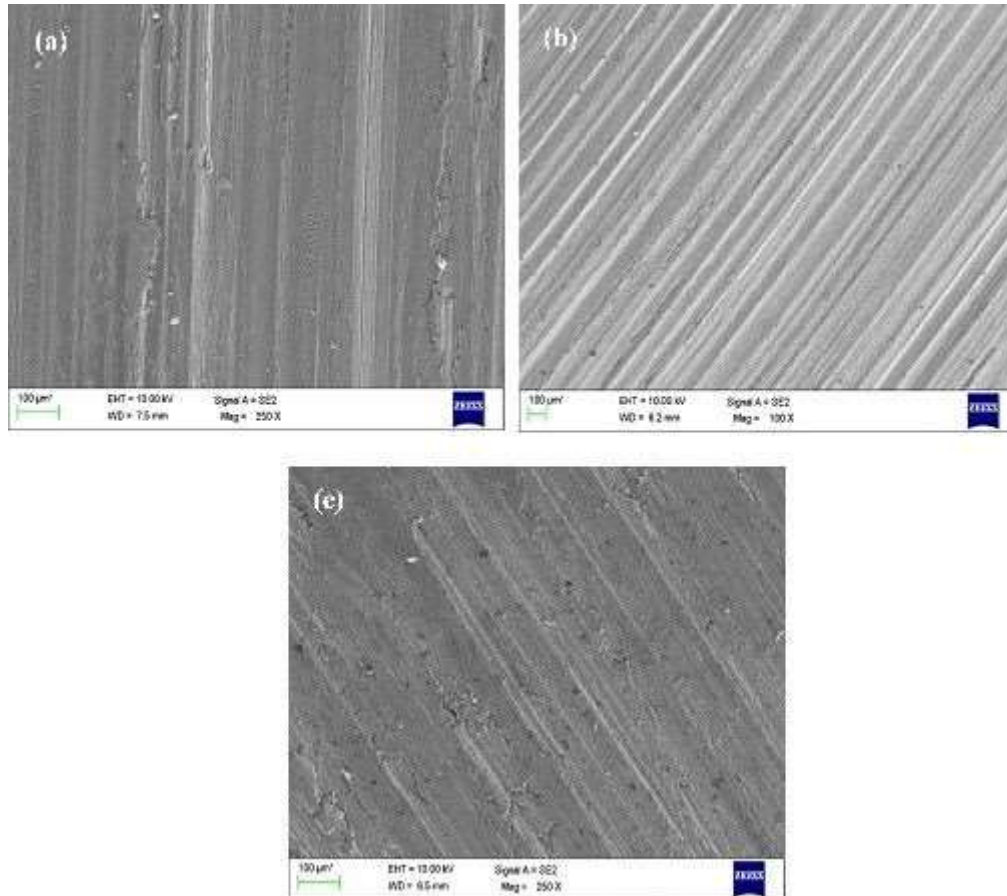


Figure 7: Typical wear surface at applied load of 39.2 N and sliding speed of 4.59 m/s and sliding distance of 1500 m (a) base alloy; (b) mono composite; (c) hybrid composite.

5 Conclusions

The following generalized conclusions were drawn from the work.

- ANOVA results indicated that sliding distance has highest influence on the wear rate followed by applied load and sliding speed in all the composites. The interactions effects have less statically significance.
- Addition of B₄C reinforcement has been found to reduce the wear rate, compared to base alloy
- Gr present in hybrid metal matrix composites increases the wear resistance of the material. Formation of protective mechanically mixed layer between pin and counter face and also smearing of graphite particles reduces the wear volume loss of the material.
- The results indicated that Gr can be considered as possible and promising filler material and as secondary

reinforcement in hybrid metal matrix composites.

- The confirmation test indicates that the error associated with of the mono and hybrid composite material less than 5%.

References

- [1] Kalaiselvan K, Murugan N, Parameswaran S. Production and characterization of AA6061-B₄C stir cast composite. *Mater Des.* 2011;32(7):4004-9.
- [2] Rajaravi C, Gopalakrishnan B, Lakshminarayanan PR. Effect of pouring temperature on cast Al/SiCp and Al/TiB₂ metal matrix composites. *J Mech Behav Mater.* 2019;28(1):162-8.
- [3] Auradi V, Rajesh GL, Kori SA. L, R. G., & Kori, S. A. Preparation and Evaluation of Mechanical Properties of 6061Al- B₄Cp Composites Produced via Two-Stage Melt Stirring. *Mater Manuf Process.* 2014;29(2):194-200.
- [4] Auradi V, Rajesh GL, Kori SA. Processing of B₄C Particulate Reinforced Aluminum 6061Matrix Composites by Melt Stirring Involving Two-step Addition. *Procedia Materials Science.* 2014;6:1068-

- 76.
- [5] Basavarajappa S, Chandramohan G, Paulo Davim J. Application of Taguchi techniques to study dry sliding wear behavior of metal matrix composites. *Mater Des.* 2007;28(4):1393-8.
- [6] Gangadharappa M, Reddappa HN, RaviKumar M, Suresh R, RaviKumar, M., & Suresh, R. Mechanical and Wear Characterization of Al6061 Red Mud Composites. *Mater Today Proc.* 2018;5(10):22384-9.
- [7] Elango G, Raghunath BK. Tribological Behavior of Hybrid (LM25Al + SiC+ TiO₂) Metal Matrix Composites. *Procedia Eng.* 2013;64:671-80.
- [8] Hemanth J. Finite Element Wear Behavior Modeling of Al/Al₂SiO₅/C Chilled Hybrid Metal Matrix Composites (CHMMCs). *Mater Sci Appl.* 2011;2(07):878-90.
- [9] Singh G, Goyal S. Dry sliding wear behavior of AA6082-T6/SiC/B4C hybrid metal matrix composites using response surface methodology. *Proceedings of the Institution of Mechanical Engineers, Part L. Journal of Materials Design and Applications.* 2007;232(11):952-64.
- [10] Gaitonde V, Karnik S, Jayaprakash M. Some Studies on Wear and Corrosion Properties of Al5083/Al₂O₃/Graphite Hybrid Composites. *J Miner Mater Charact Eng.* 2012;11(7):695-703.
- [11] Sathish T, Saravanan S, Vijayan V. Effect of reinforced aluminium alloy LM30 with pure ceramic particles to evaluate hardness and wear properties. *Mater Res Innov.* 2020;24(3):1-4.
- [12] Xavier LF, Suresh P. Wear Behavior of Aluminium Metal Matrix Composite Prepared from Industrial Waste. *The Sci World J.* 2016;6538345: 1-8.
- [13] Baradeswaran A, Perumal AE. Study on mechanical and wear properties of Al 7075/Al₂O₃/graphite hybrid composites. *Compos, Part B Eng.* 2014;56:464-71.
- [14] Siddesh Kumar NG, Suresh R, Shiva Shankar GS. High Temperature Wear Behavior of Al2219/n-B4C/MoS₂ Hybrid Metal Matrix Composites. *Composite Communications.* 2020;19:61-73.
- [15] Chand S, Chandrasekhar P. Influence of B4C/BN on solid particle erosion of AL6061 metal matrix hybrid composite fabricated through powder metallurgy technique. *Ceram Int.* 2020;46(11):17621-30.
- [16] Şimşek İ. the effect of B4C amount on wear behaviors of Al-Graphite/B4C hybrid composites produced by mechanical alloying. *Journal of Boron.* 2019;4:100-6.
- [17] Miloradović N, Vujanac R, Mitrović S, Miloradovic D. Dry Sliding Wear Performance of ZA27/SiC/Graphite Composites. *Metals (Basel).* 2019;9(717):1-13.
- [18] Alidokht SA, Abdollah-zadeh A, Soleymani S, Assadi H. Microstructure and tribological performance of an aluminium alloy based hybrid composite produced by friction stir processing. *Mater Des.* 2011;32(5):2727-33.
- [19] Ranganath G, Sharma SC, Krishna M. Effect of Garnet Particle on the Mechanical and Microstructural Properties of ZA-27 Alloy Composites. *J Mech Behav Mater.* 2001;12(4):239-54.
- [20] Dwivedi SP, Dwivedi G. Utilization of RHA in development of green composite material using RSM. *J Mech Behav Mater.* 2019;28(1):20-8.