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Analysis of dry sliding wear behavior of mono composites and hybrid composites

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Abstract: *Metal Matrix Composites (MMCs) have gained significant attention for their enhanced mechanical properties and wear resistance in industrial applications. This study investigates the dry sliding wear behavior of mono-composite (Al2219/B4C) and hybrid composite (Al2219/B4C/Gr) using statistical analysis to understand their tribological performance under different operating conditions.*

Experimental wear tests are conducted using a pin-on-disc tribometer under varying loads, sliding speeds, and sliding distances. Response Surface Methodology (RSM) and Analysis of Variance (ANOVA) are applied to evaluate the influence of process parameters on wear rate and coefficient of friction. Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS) are used to examine the worn surfaces and identify dominant wear mechanisms.

The results indicate that the hybrid composite (Al2219/B4C/Gr) exhibits lower wear rates and friction coefficients compared to the mono-composite due to the lubricating effect of graphite (Gr). Statistical modeling confirms that load and sliding speed significantly influence wear behavior, with wear following a mixed mechanism of abrasion and delamination. This study provides valuable insights into optimizing MMC compositions for aerospace, automotive, and structural applications requiring superior wear resistance.

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

I. 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 tailor able to precise applications due to their properties like stiffness and specific strength. Aluminium metal matrix composites are advance 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 (B_4C), titanium diboride (TiB_2), alumina (Al_2O_3), silicon carbide (SiC) particles and so on. Composite materials possess variable strengthening mech- anisms 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 B_4C particles are very hard, high stiffness, low Thermal conductivity and these ceramic particles reinforcing with metal matrix are widely used in armor 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 Al_2O_3, SiC, TiB_2 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] re- ports 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/TiO_2) 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 TiO_2 particle reinforcement.

Hemanth *et al.* [8] carried an investigation on mechanical properties and wear behaviours of kaolinite (Al_2SiO_5) and carbon(C) particles reinforced chilled metal matrix composites (CMMCs) by experimental method and com- pared with finite element (FE) simulation method. They found that the cryogenic chilled MMCs with Al_2SiO_5-9% and C-3% reinforced content provides high strength, hard- ness 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 analyzed. The coefficient of friction is directly proportional to sliding speed and applied load. Regression modelling for wear rate composites reveals that inversely proportional to slid- ing 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 Al_2O_3 and Gr hybrid composites. Experimental results on Al_2O_3 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, B_4C and Gr using dry sliding test. The analysis results show that wear rate decreases with increases of SiC and B_4C reinforcement percentage in the composites. Xavier *et al.*

[12] studied the dry sliding wear behavior of Al-MMC rein- forced 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 hard- ness 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-B_4C/MoS_2) using dry sliding wear test. The test results on n-B_4C and MoS_2as a secondary reinforcement in Al-2219 matrix indicates the high wear resistance and high hardness when compared to mono composite (Al2219/n-B_4C). 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 B_4C and BN reinforcement in Al6061 alloyimproves the wear resistance of the composite. Şimşek [16] studied the effect of B4C and Gr rein- forcements on wear behaviours of Al-Graphite/B4C hy- brid composite. The results indicated that Gr reinforce- ment 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 hy- brid composites. They observed that the hybrid composite (ZA27/%SiC/%Gr) was higher wear resistance when com- pared to mono composite (ZA27/%SiC). It is mainly due to the solid lubrication obtained by the existence of Gr filmon 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 percent- age 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/B_4C) and collective (hybrid compos- ite: Al/B_4C/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 op- timized values. Surface examinations of wear test speci- mens have been analysed through SEM and XRD analysis.

II. Experimental procedures

2.1 Materials and method

The Al2219 matrix material was chosen because of excel- lent properties such as high strength, high fracture tough- ness, 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. B_4C of average 90 micron size of particles and secondary reinforcement element Gr of 30 micron size were used as reinforcement materials. Two types of composites were prepared; one with mono composite (Al2219 + 8% B_4C) and second one with hybrid composite (Al2219+8% B_4C+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 B_4C and Gr particles were added into the molten matrix alloy. Super-heated compos- ite slurry was poured in to the mould of 12 mm diameterand 100 mm length pre-heated die.

Finally, the specimens were cleaned and pre- machined with CNC turning machine. For the microstruc- ture 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% B_4C) and hybrid composite (Al2219+8% B_4C+3% Gr) are as shown in Figure 1. For the mono composite shows that uniform distribution of B_4C 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 (K_2TiF_6) along with the reinforcement particles gives good wettability between Al and B_4C. Use of halide salt (K_2TiF_6) during casting has wettability and bonding between Al and B_4C and also uni- form dispersion of reinforcing B_4C particles in Al matrix material. K and F present in K_2TiF_6 contribute for removal of oxide on the Al surface. The reason is that the halide salt processed with B_4C particles and produces Ti compound surround the B_4C particle surface. These B_4C particles con- tinuous layers of Ti confirm the products of TiC and TiB_2. 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

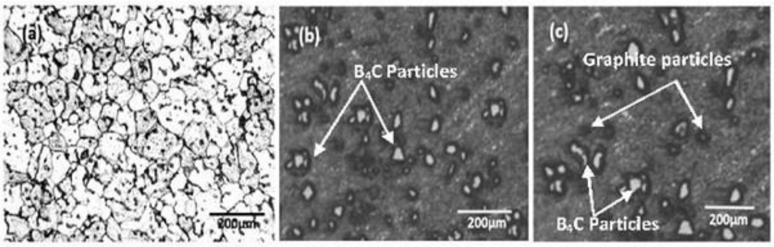

Figure 1: (a) Microstructure of base alloy (Al2219); (b) mono composite (Al2219+8%B4C); (c) hybrid composite (Al2219+8% B4C+3%Gr)

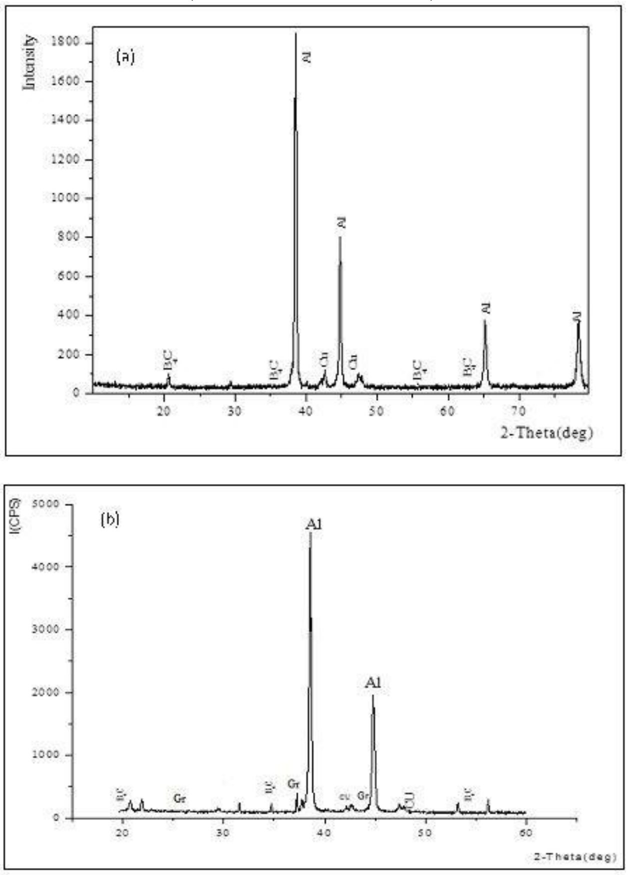

Figure 2: XRD profiles of (a) mono composite (Al2219+8% B_4C); (b)hybrid composite (Al2219+8% B_4C+3% Gr)

along with B_4C 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 B_4C 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

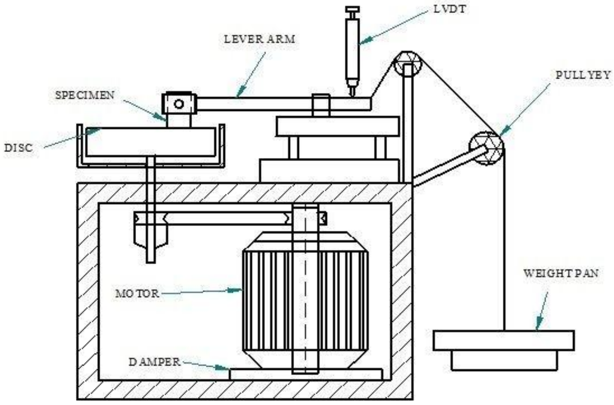

Figure 3: Schematic diagram of wear test apparatus

Table 2: Process parameters fixed with their levels

Level	Sliding speed (m/s)	Load (N)	Sliding distance (m)
1	1.53	9.81	500
2	3.06	19.6	1000
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_4C (mm^3/m) (10^{-3})	Wear rate 8% B_4C + 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 L_{27} 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 us- ing 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. Trail runs were performed to find upper and lower limits for the identi- fied 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.

III. Results and discussion

The main objective is to study the influence of sliding dis- tance (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 (L_{27}) orthogonal array and it was employed to ac- quire 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 car- ried out using smaller is the better criterion and same re- sponse. 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%

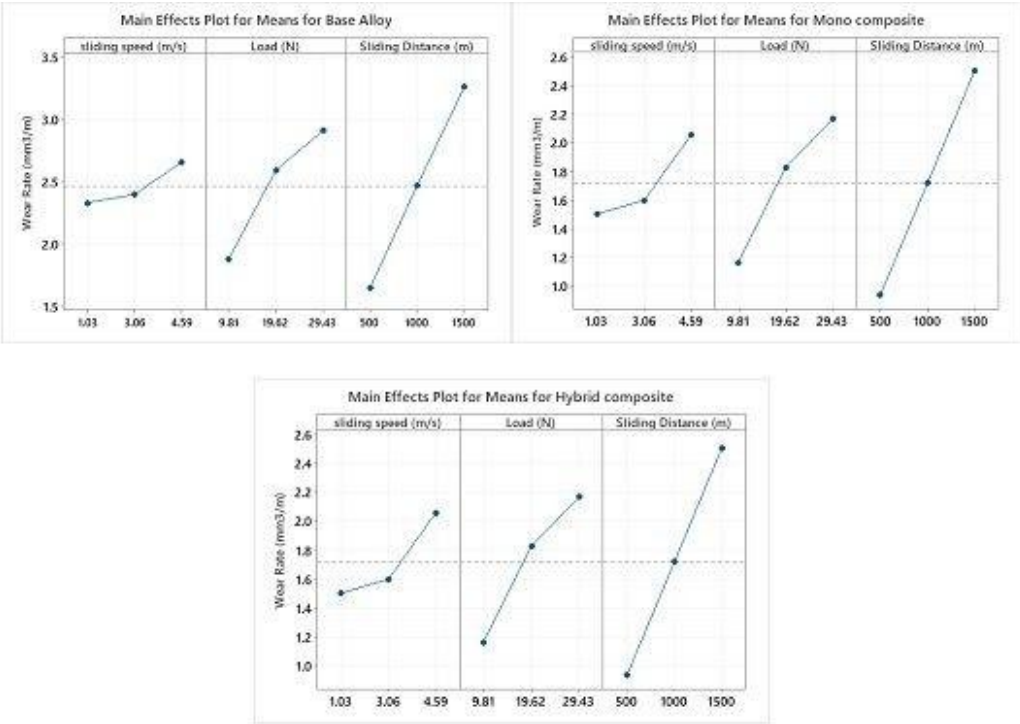

Figure 4: Main effects plots for wear rate of (a) base alloy; (b) mono composite; (c) hybrid composite material

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 ef-fects plots (Figure 4).

3.1 ANOVA analysis results

Table 4 shows the ANOVA analysis results for wear behav- ior 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% B_4C), the sliding distance (56.51%), applied load (23.94%) and sliding speed (8.04%) has great influence on wear rate (Table 5). Whereas for hy- brid composite (Al2219+8% B_4C+3% Gr), sliding distance (53.64%), applied load (20.82%) and sliding speed (15.51%) have influences on wear rate (Table 6). However, the in- teractions 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 slid- ing speed on wear rate in all the composites. However, the influence of graphite particle in hybrid composite in- crease in wear resistance when compared to mono compos- ite and base alloy materials. Furthermore, in hybrid com- posites (Al2219+8% B_4C+3% Gr) wear resistance is more than base alloy (Al2219) and mono composite (Al2219+8% B_4C) because of solid lubricant property. Graphite acts as a self-lubricating material, for that wear rate initially con- trolled. 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 compos- ite 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 forma- tion of mechanically mixed layer. This causes weakened tribo-layer formation on the surface of hybrid composite material. Similar results were found in Basavarajappa *etal.* [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 Fig- ures 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 in- creases 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 mate- rial softening effect is more increased in sliding distanceas observed in Figure 4(a).

In case of mono composite, the reinforcement of hard B_4C 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 delamina- tion for enhancement of wear rate. The wear rate of com- posites was much lower when compared to pure base al- loy. The hybrid composite has less wear rate while com- pared to mono and pure base alloy. In Al2219 alloy sub- surface 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 delamina- tion wear also increases. The wear surface of base alloy at higher load of 40 N shows the serrated surface layer. Sur- face 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 B_4C parti- cles increase the hardness of the material. Increase in hard- ness attributed improvement in wear rate and seizure resis- tance of materials. The presence of hard B4C particles in- creases 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 andact as a strong barrier for dislocation motion.

In hybrid composite containing graphite particles de- creases the wear rate due to solid lubricating property of graphite. The Gr particles smeared from contact sur- face 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 en- hances contact load by work hardening effect. As the load increases dislocation move past the particles pileup dislo- cation at the grain boundary and stress concentration initi- ates the delamination crack at the particle or matrix mate- rial 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 dis- tance for all the composites. However for hybrid compos- ites less wear rate is observed compare to mono and Al2219 alloy. In case of Al2219 there is no strengthening mecha- nism 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 incorpora- tion of B4C particles in Al2219 alloy improves the wear re- sistance 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 dis- tance increases further B4C particles which are held to the pin are subjected to less wear when compared to base al- loy. 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 com- posite 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%B_4C)

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%B_4C+3%Gr)

Level (S)	Sliding speed	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

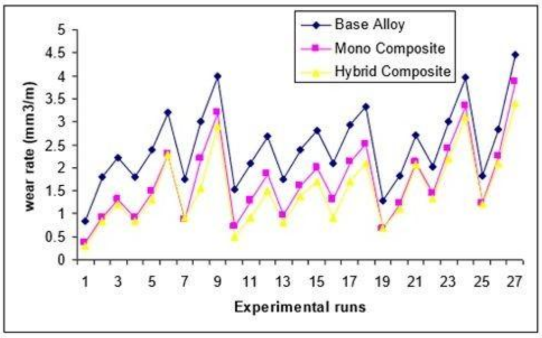

Figure 5: Comparison of experimental results for base alloy (Al2219), mono composite (Al2219+8% B4C) and hybrid composite(Al2219+8% B4C+3% Gr) materials

mono composite are higher than hybrid composite. It in- dicates that graphite (Gr) is considered as one promisingfiller material and as secondary reinforcement in metal ma-trix composites.

3.2 Linear regression models

A linear regression analysis attempts to model the rela- tionship between two or more predictor variables and re- sponse variable by fitting a linear equation to the observed data. To establish the correlation between the wear pa- rameters 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%B_4C) and hybrid Al2219+8%B_4C+3%Gr composites are given in Eq. (1), (2) and (3), respectively.

Wear rate of base alloy = −0.211 + 0.106(S) (1)
+ 0.0324(L) + 0.00161(D) + 0.00012(S*L)
+ 0.00003S*D) + 0.000025(L*D)

Wear rate of mono composite = −1.13 + 0.181(S) (2)
+ 0.0317(L) + 0.00157(D) + 0.0001251(S*L)
+ 0.000028(S*D) + 0.000022(L*D)
Wear rate of hybrid composite = −1.09 (3)
+ 0.202(S) + 0.0247(L) + 0.00146(D) + 0.000118(S*L)
+ 0.0000246S*D) + 0.0000221(L*D)

3.3 Confirmation test

Confirmation tests were conducted according to the opti- mized values (Table 7, 8 and 9) and Main effects plots (Fig- ure 4) are shown in Table 10. The experiments were con- ducted 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 re- sults confirms the reasonable degree of approximation.

IV. Microstructural analysis of wearsurface

Figure 6 shows the SEM images of the worn surfaces of base alloy (Al2219), mono composite (Al2219+8% B_4C) and hybrid composite (Al2219+8% B_4C+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 mor- phology of the specimen is as shown in Figure 6(a). The image shows that softening of the Al2219 at interface tem- perature and forms severe plastic deformation. And also observed the high strain rate subsurface deformation and delamination. For mono composites (Al2219+8% B_4C) con- sists of B_4C particles improves the wear resistance when comparison to unreinforced alloy. At lesser load grooves are formed shallow and less material removable is ob- served (Figure 6(b)). These asperities are plastically de- formed 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 ma- terial 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% B_4C+3% Gr) formation of tribo-layer in between contact surfaces. Along with pro- tective layer graphite smears out and minimize wear loss of the composite at selected parameters. The asperities be- tween specimen and counter face formed under the in- fluence of applied load. In the beginning, specimen and counter face are allied to fill the valley of the matrix mate- rial. 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_4C)
3	5.35	44.1	2000	Hybrid composite(Al2219+8%B_4C+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

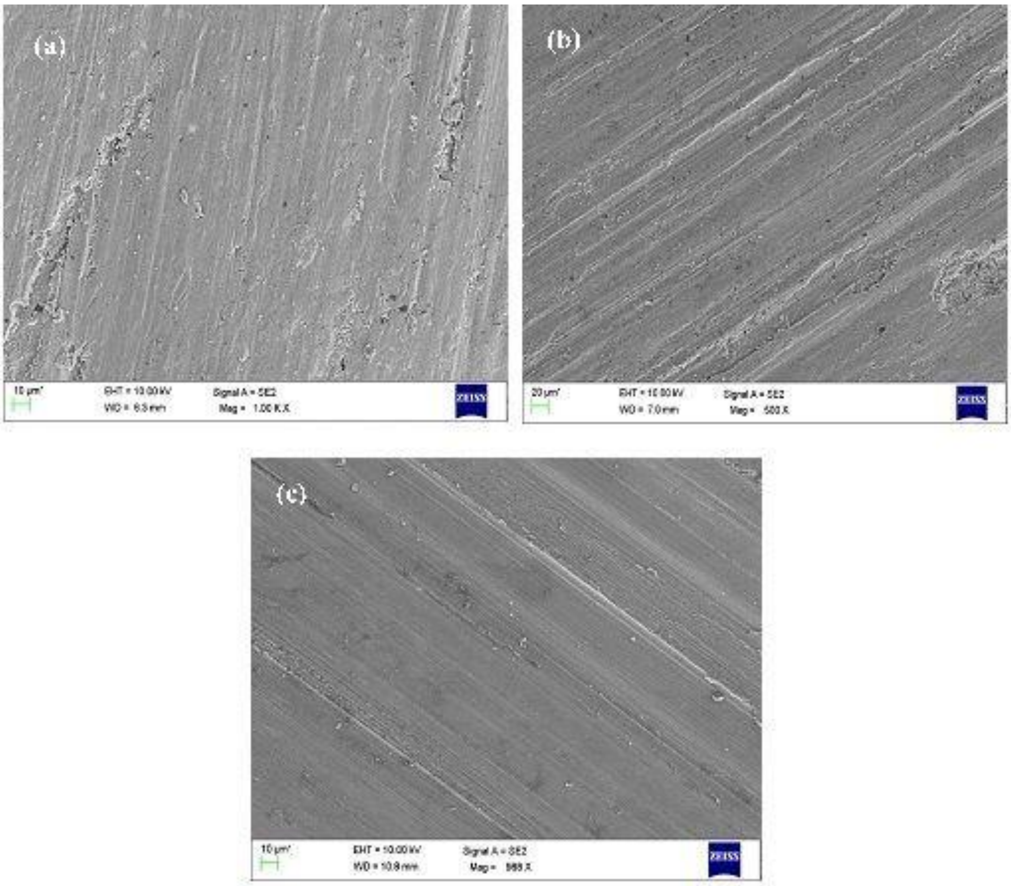

Figure 6: Typical wear surface at applied load of 19.6 N and sliding speed of 3.06 m/s and sliding distance of 1000 m (a) base alloy; (b)mono composite; (c) hybrid composite.

on matrix surfaces route a very fine debris. The presence of Gr forms a protective mechanically mixed layer (MML) be-tween 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 suface of mono composite (Al2219+8% B_4C) material with large number of deep abrasive grooves presence along the sliding direction. It is mainly because of high pressure and temperature, hard B_4C 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% B_4C+3%Gr) material. In Al2219+8% B_4C+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 dis-tance, abrasive wear causes troughs and straight grooves along the sliding direction. Later stage, formation of gath- ered laminate layers occurs. It is due to increase of plastic deformation and high wear causes destruction of the sur- face in depth and some indigenous departure of the ma- trix material occurs. It can be revealed that addition of B_4C 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 B_4C and Gr particles reinforcement increases the wear resistance and volume loss of the material and also establishment of pro- tective layer between specimen and counter face. The can be concluded that graphite (Gr) particles can be consid- ered as one of the promising filler materials and as sec- ondary reinforcement in hybrid metal matrix composites.

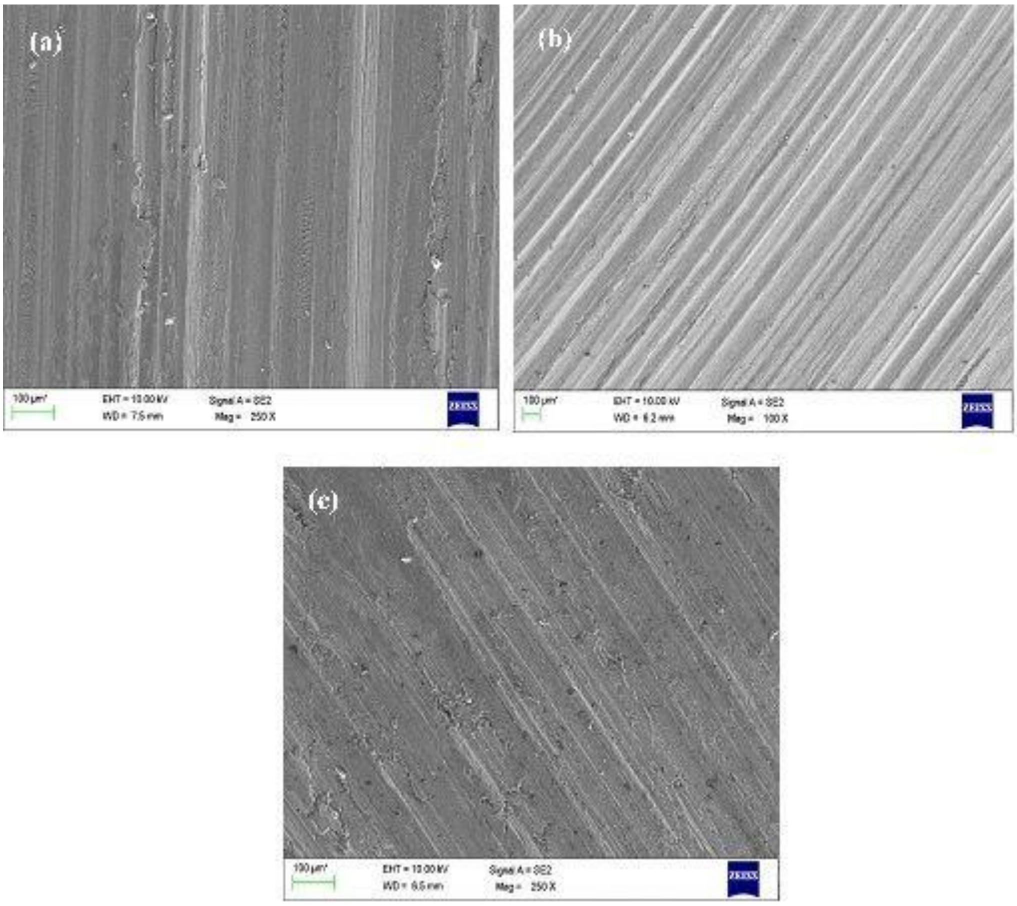

Figure 7: Typical wear surface at applied load of 39.2 N and sliding speed of 4.59 m/s and sliding distance of 1500 m (a) base alloy; (b)mono composite; (c) hybrid composite.

V. Conclusions

The fallowing generalized conclusions were drawn fromthe 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 B_4C reinforcement has been found to re-duce the wear rate, compared to base alloy
- Gr present in hybrid metal matrix composites in- creases the wear resistance of the material. Forma- tion of protective mechanically mixed layer between pin and counter face and also smearing of graphiteparticles 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%.

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