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RESEARCH

Evaluation of Dry Sliding Wear Characteristics of LM 13 Al/B_4C Composites

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A B S T R A C T

The present paper labels the wear behaviour of the manufactured LM 13 aluminium/B_4C metal matrix composites synthesized by means of liquid metallurgy technique. The B_4C particles with size 33 μm diversified for the range of 0, 4, 8 and 12 wt-% were incorporated in the composite. The wear behaviour of the composites was studied as per L_{16} orthogonal array using pin-on-disc tribometer for various sliding conditions by varying the parameters such as load, velocity, sliding distance and wt-% of the reinforcement. Smaller-the-better characteristic was selected as the objective of the developed model and the optimum level of each parameter was detected. The influence of the parameters on the wear rate was known through analysis of variance. Regression model was developed and checked for adequacy using confirmation experiments. Scanning electron microscope analysis was done to study the worn morphologies of composite surface. The experimental results disclose that load was the major influencing parameter on the wear behaviour followed by wt-% of reinforcement, velocity and sliding distance. The worn-out surface interprets that rise in load yields a transition in the wear mechanism. The confirmatory results evident that Taguchi's design as efficient statistical model by supporting the regression results with less error.

1. INTRODUCTION

Metal matrix composites (MMCs) have several advantages like high strength, less weight, high wear resistance over the monolithic metals which makes them to use in several automotive and industrial applications. Particle reinforced MMCs has numerous advantages and it was fabricated easily with less cost compared to fibre reinforced MMCs [1,2]. Particulate reinforced MMCs were raised as the latent materials for the automotive tribological applications predominantly for pistons, brake drum, cylinder liners, connecting rods and cylinder block because of its high wear resistance and less weight. This assists the automotive field to achieve improved fuel efficiency that helps in saving billions in a year [3,4].

There was global need of reducing the wear in order to reduce the usage of material resources and wastage of energy. This controlling of wear should be considered carefully from the basis of selecting the alloy composition, reinforcement and also the processing methods [5]. This drives the researchers to bring innovation in the automotive field by developing the alumina (Al_2O_3) reinforced hypereutectic aluminium alloy (25 % silicon) cylinder liners. This aluminium composite liner becomes the promising material for the substantial decline in weight than the commercially used cast iron liners and aids in accomplishing greater wear resistance [6].

Researchers explained that, discovering the origin of damage in the automotive components assists in concentrating property improvement in that area, which substantially improves the lifetime of the component. This brings the consideration of the casting process which hinders in achieving the property in the particular part of the component [7]. The application of the aluminium composites in making components was increasing every year. Therefore, the burden falls in choosing production route of the aluminium composites. Solid state handling or liquid state handling was generally used for the production of aluminium composites. Stir casting was one of the most commonly used processing route among other casting techniques such as squeeze casting, compo-casting etc., for synthesizing composites [8]. Literatures apparently show that numerous particulates such as silicon carbide (SiC), Al_2O_3, aluminium nitride (AlN) etc., were successfully processed through stir casting technique [9,10].

The researchers were focused on the tribological behaviour of the stir cast composites by considering various process parameters as well as working conditions [11]. The effect of process parameters and the addition of reinforcement on the dry sliding wear of the composites were investigated vastly [12,13] and explained that incorporation of hard secondary constituent in the matrix significantly improves the wear resistance [14]. Adhesive wear behaviour of Al 4147 alloy and Al 4147/ boron carbide (B_4C) composite fabricated through liquid metallurgy technique has been investigated and concluded that matrix alloy exhibits severe wear regime whereas the B_4C reinforced composite reveals only mild wear regime at the same wear condition [15]. Different volume fraction of hard coated B_4C reinforced Al 2024 matrix fabricated through squeeze casting process has been studied for its wear behaviour and reported that B_4C particles protruded over the matrix surface protects the matrix from wear by acting as the load bearing elements. It was also stated that wear resistance of the composite increased with increasing the reinforcement content [16].

The reports further stating that, controlling of factors in optimum manner outcomes in less wear of the composites. So, a need arises in controlling the parameters and obtaining the output in a logical manner, which lessens the digit of experiments even though the number of parameter increases. This statistical way of analysis moderates the consumption of time and cost of the experimental process [17]. Reports were enlightening that Taguchi's design of experiments (DOE) methodology was systematic and efficient way to analyse the effect of parameters on the response with the help of orthogonal arrays [18]. Regression analysis was carried out to validate the efficiency of the developed statistical model by relating the influence of parameters obtained in analysis of variance (ANOVA) with the response [19].

There were much researches elucidating the dry sliding wear behaviour of the composites reinforced with SiC, Al_2O_3, AlN etc., The exposure on B_4C particles reinforced aluminium composites was not that much in the present scenario. Therefore, the current study addresses the exploration on dry sliding wear behaviour of the aluminium/B_4C composites through Taguchi's statistical model and checking the efficiency of the developed model through regression analysis.

2. TEST MATERIALS

The LM 13 aluminium alloy having density of 2.70 gm/cm^3 was selected as the base matrix and B_4C (33 μm) was selected as reinforcement for the different wt-% of 0, 4, 8 and 12. The applications of LM 13 aluminium alloy were pulleys, pistons, sheaves and bearings. The high silicon content (10.9 %) in this alloy makes it feasible for high wear resistance applications.

The B_4C particle with density of 2.51 gm/cm^3 was found as the third hardest element next to boron nitride and diamond. It has the hardness of 9.497 on Moh's scale, obviously which shows that B_4C was one of the hardest reinforcement employed commonly in the production of MMCs. The chemical composition of the LM13 aluminium alloy was indicated in Table 1.

Table 1. Chemical composition of the LM 13 aluminium alloy.

Chemical composition	(%)
Al	83.39
Si	10.9
Fe	0.527
Cu	1.31
Mg	1.05
Ni	2.32
Others (Mn, Cr, Zn, Sn, Ti, Pb, Ca)	0.494

3. FABRICATION PROCESS

The aluminium MMCs reinforced with B_4C particles (0, 4, 8 and 12 wt-%) were manufactured through liquid metallurgy route using the electric resistance furnace under controlled inert gas atmosphere. The procurement of LM 13 aluminium alloy was made in the form of ingots. The ingots were sliced to small pieces and graphite crucible was used for loading the pieces in the furnace. The furnace was equipped with stirrer setup and temperature regulator along with indicator. The temperature was fixed with respective to the melting temperature of LM 13 aluminium alloy to melt the alloy. The wetting property of the reinforcements was improved by oxidising their surfaces through preheating. After melting of alloy, the preheated particles were added to the molten metal. The temperature at the heating chamber was maintained at 760 °C and the mechanical means of stirring was done for 5 min for the average stirring speed of 300 rpm in the fully liquid state condition of the molten metal. This stirring process creates a vortex which neglects the unnecessary gas content that arises as the defect in the casting and it enables uniform distribution of the B_4C particles in the molten metal. Permanent metallic steel mould having holes of size 25 mm diameter and 150 mm length was preheated in order to reduce the temperature difference between pouring and preheated temperature. This preheating increases the fluidity of the molten metal and thereby reduces the thermal defects. The molten metal was poured manually at the temperature of 760 °C into the mould under gravity. Then the molten metal is let to cool to room temperature to eject the cylindrical cast specimens from the mould. The analogous method was followed for manufacturing the composites reinforced with different wt-% of B_4C particles.

4. EXPERIMENTAL PROCESS

The sliding wear characteristics of the unreinforced alloy (0 wt-%) and the composites (4, 8, 12 wt-%) were studied at room temperature utilising pin-on-disc machine (TR–20, Ducom–India) in dry condition. The cylindrical test pins of length 35 mm and diameter of 12 mm were machined from the cast specimen and tested against rotating steel disc (EN–32, 65 HRC) by applying the load. The specimens were grinded at the edges for the removal of burrs. The machining marks on the test pins were removed by rubbing against the SiC emery papers. The steel disc was polished regularly to have a fresh interaction with the surface of the test pins prior to experiment. The experiments were planned with the assistance of L_{16} orthogonal array generated for the selected four parameters and their four levels. The selected parameters and their levels for the experiment were shown in Table 2.

Table 2. Parameters and their levels.

S. No	Load (N)	Velocity (m/s)	Sliding distance (m)	Reinforcemen t(wt-%)
1	10	1	500	0
2	20	2	1000	4
3	30	3	1500	8
4	40	4	2000	12

The wear rate (response) was studied as the function of selected parameters. The steady state wear rate was calculated using the formula (1):

$$W = \frac{M}{\rho D} \tag{1}$$

Where W is the steady state wear rate (mm^3/m), M is mass loss (g), ρ is density (g/mm^3) and D is the sliding distance (m).

5. RESULTS AND DISCUSSION

The explanatory sections focused on the topics of wear characteristics of composites, Analysis of signal-to-noise (S/N) ratio, ANOVA for wear rate, scanning electron microscope (SEM) examination and linear regression model.

5.1 Wear characteristics of composites

The wear behaviour of the composites was investigated as per the plan of experiments generated through the Taguchi's design and results were analysed employing the statistical software Minitab 15, which was commonly utilised for engineering purposes. The wear rate was studied as response as the function of the parameters such as load, velocity, sliding distance and wt-% of reinforcement. The computed results for L_{16} orthogonal array and the S/N ratios were shown in Table 3. The plots for wear rate and the S/N ratios were indicated in Figs. 1 and 2 respectively.

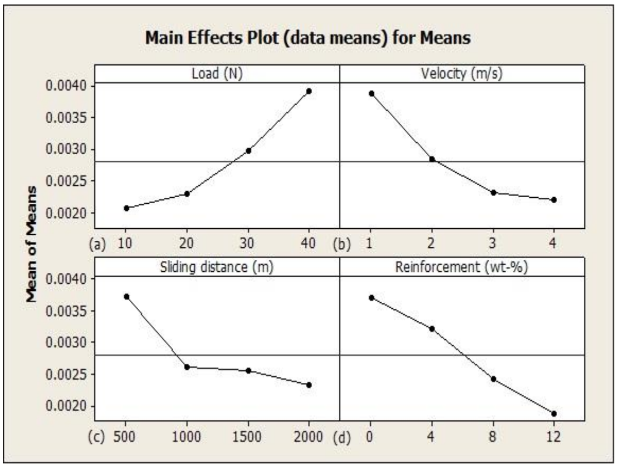

Fig 1. Main effect plots for means–Wear rate.

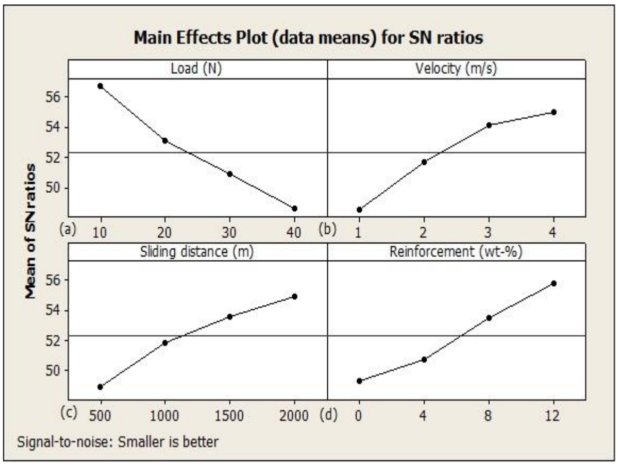

Fig 2. Main effect plots for S/N ratio–Wear rate.

The wear rate variation for the various levels of each parameter was displayed in Fig. 1. The steady state wear rate was calculated here since the total wear rate was not good for comparison of wear performance of the materials. The wear rate was observed to be normally increasing when load increases (Fig. 1a), as likely observed in many reports [20].

This was due to the increase in the contact pressure at the interface of the specimen and the counter face when load was increased. The wear rate was found increasing gradually because of the increase in load of equal steps.

Table 3. Experimental results and their S/N ratios.

S.No	Load (N)	Velocity (m/s)	Sliding distance (m)	Reinforcement (wt-%)	Wear rate (mm³/m)	S/N ratio (db)
1	10	1	500	0	0.0048700	46.2494
2	10	2	1000	4	0.0019655	54.1305
3	10	3	1500	8	0.0008447	61.4660
4	10	4	2000	12	0.0005523	65.1565
5	20	1	1000	8	0.0032713	49.7056
6	20	2	500	12	0.0022453	52.9745
7	20	3	2000	0	0.0018960	54.4432
8	20	4	1500	4	0.0017500	55.1392
9	30	1	1500	12	0.0025412	51.8992
10	30	2	2000	8	0.0020560	53.7395
11	30	3	500	4	0.0042994	47.3318
12	30	4	1000	0	0.0029880	50.4924
13	40	1	2000	4	0.0048537	46.2785
14	40	2	1500	0	0.0050740	45.8930
15	40	3	1000	12	0.0022045	53.1338
16	40	4	500	8	0.0035277	49.0502

The wear was found mild at the load of 10 N and it was normal at the range of 20-30 N then it gets transition and was high at the load of 40 N, whereas the similar pattern was observed [21]. The wear rate found to be decreasing when the sliding velocity increases on all the composite specimens (Fig. 1b), as this was attributed to transfer of materials between specimen and the counter face due to high interface temperature developed at high velocity. This transfer of material forms a protective layer on the surface which reduces the metal to metal contact thereby reduces the wear rate and same behaviour is observed [22].

The indication of decreasing wear rate for the increase in sliding distance (Fig. 1c) was attributed to the running in process and steady state process. The protruded hard asperities on the surface of the specimen and the counter surface gets contacted and fractured at the initial sliding distance which results in high wear rate. The asperities gets smoothened and flattened after running for some considerable sliding distance and produces uniform contact which causes the wear rate to get stabilized. After this condition, wear was found merely steady and this depends upon the fluctuations in the pressure exerted by the applied load, where same mechanism was observed [23].

The slope for wear rate was found decreasing for the variation in reinforcement (Fig. 1d). This demonstrates that the wear behaviour of the composites was found improved significantly with the addition of B_4C particles as reinforcement. The reinforcement particles bear the impact produced by load and outcomes in less wear rate. This ensures that, there was uniform distribution and good interfacial bonding of the reinforcement particles with the matrix was attained through the liquid metallurgy route. This bonding of particles resists the pull out of the reinforcement particles and results in less wear rate.

The matrix alloy being as a softer surface gets easily deformed at 0 wt-% reinforced condition, results in heavy wear rate and the contact area of the matrix with the counter surface was considerably reduced at highly reinforced (12 wt-%) condition, results in less wear rate. This was attributed to the hardness of the B_4C reinforcement particles, as the hardness was directly related to the wear resistance. Thus the addition of wt-% of reinforcement benefits the composites in attaining high wear resistance, the similar criteria attained [24].

The optimum combination of the parameters was witnessed from Figs. 2a–d, as load of 10 N, velocity of 4 m/s, sliding distance of 2000 m and reinforcement of 12 wt-% consequences in less wear rate. Therefore to achieve less wear rate, load should keep minimum and parameters such as velocity, sliding distance and wt-% of reinforcement should be at their maximum position.

5.2 Analysis of signal-to-noise ratio

The S/N response table (Table 4) was developed by the Minitab software from the obtained S/N ratios for their corresponding experimental wear values. This table 4, shows the influencing order of the parameters such as load, velocity, sliding distance and wt-% of reinforcement on the wear rate.

The influence of the parameter was determined through the delta value. The difference between the highest and lowest S/N ratio of the parameter provides the delta value. The higher delta value indicates the more influence parameter. The impact of load on the wear rate was found high whereas the impact of wt-% reinforcement, velocity and sliding distance on the wear rate was found next to load in the sequential order.

Table 4. Response table for S/N ratio–*Smaller-the-better.*

Level	Load (N)	Velocity(m/s)	Sliding distance (m)	Reinforcement (wt-%)
1	56.75	48.53	48.90	49.27
2	53.07	51.68	51.87	50.72
3	50.87	54.09	53.60	53.49
4	48.59	54.96	54.90	55.79
Delta	8.16	6.43	6.00	6.52
Rank	1	3	4	2

5.3 Analysis of variance for wear rate

The parameters significantly affecting the quality characteristics was investigated through ANOVA and displayed in Table 5.

Table 5. ANOVA for wear rate (mm^3/m).

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Pct (%)
Load (N)	3	0.0000083	0.0000083	0.0000028	5.77	0.092	28.13
Velocity (m/s)	3	0.0000071	0.0000071	0.0000024	4.91	0.112	24.06
Sliding distance (m)	3	0.0000047	0.0000047	0.0000016	3.29	0.177	15.93
Reinforcement (wt-%)	3	0.0000079	0.0000079	0.0000026	5.47	0.098	26.77
Error	3	0.0000014	0.0000014	0.0000005			4.74
Total	15	0.0000295					

Note: DF–degrees of freedom; Seq SS–sequential sum of squares; Adj SS–adjacent sum of squares; Adj MS–adjacent mean squares; Pct–percentage.

The total variability of the S/N ratios into contributions by each individual parameter was done by ANOVA. The variability of the parameter was determined through the sum of squares deviation to the total sum of squares. The analysis was conducted for the confidence limit of 95 % and 5 % of significance level. The P value examines the significance of all the parameters, which indicates that the parameter which has least P value or P value less than 0.05 contributes more on the wear behaviour.

Thus, from Table 5, it was concluded that load has the major influence of 28.13 % among the parameters. The percentage contribution of all the parameters on the quality characteristics was observed from the Table 5, that load has the major contribution on the wear behaviour followed by reinforcement (26.77 %), velocity (24.06 %) and sliding distance (15.93 %).

5.4 Scanning electron microscope examination

The various worn-out surfaces subjected to SEM examination were shown in Figs. 3a–d. The worn-out surfaces were selected for examination by considering the significance of the parameters on the wear behaviour of the composites.

Since load was found as the dominant parameter on the wear behaviour, the transition in the state of the wear mechanism was detailed here for the increase in load at constant reinforced condition of 4 wt-%. This provides guide for controlling the major parameter when concentrating on the wear behaviour of the composites.

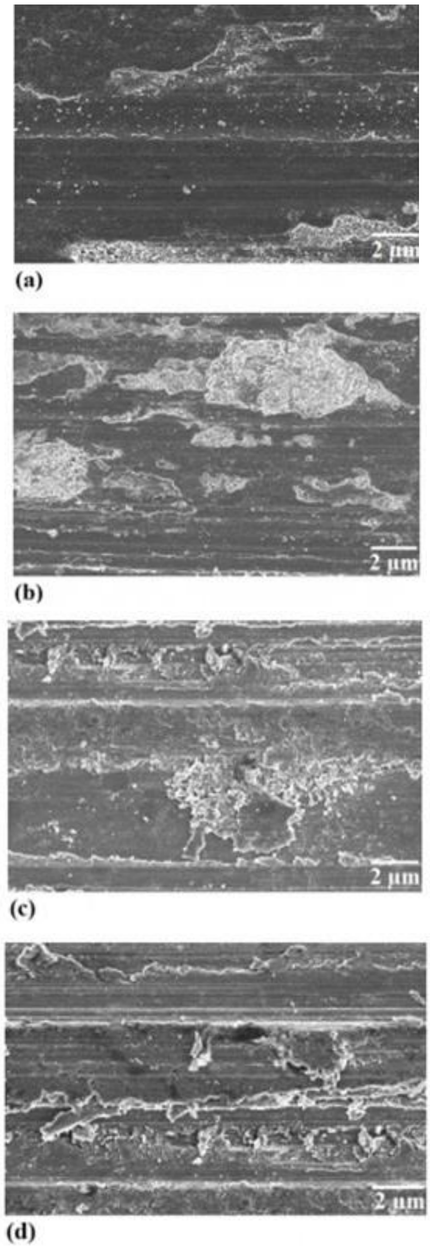

Fig 3. SEM examination of the worn-out surfaces at:
(a) L = 10 N, V = 2 m/s, D = 1000 m, R = 4 wt-%
(b) L = 20 N, V = 4 m/s, D = 1500 m, R = 4 wt-%
(c) L = 30 N, V = 3 m /s, D = 500 m, R = 4 wt-%
(d) L = 40 N, V = 1 m/s, D = 2000 m, R = 4 wt-%

Figure. 3a, reveals smaller scratches with mild wear regime on the worn-out surface as this was related to the less interfacing contact at low load (10 N). When the load increased to 20 N (Fig. 3b), a slight increase in wear rate was detected as more intact was produced. The worn-out surface reveals increased number of grooves which ensures that mild wear takes a transition on increasing the load. On further increase of load to 30 N (Fig. 3c), the continuous surface grooving was observed as the result of removal of particles from the counter surface. The particle removed from counter face acts as a third body material which slides in the direction of sliding along with the counter face.

This shows that transition fully occurred and the wear turns to severe in the composites when increasing the load and results in seizure of material. This surface also reveals the crack formation across the surface indicates the high wear regime. At high load (Fig. 3d) condition, the surface gets more intact than load of 30 N, which highly deforms as there was increase in temperature on the surface. This surface also reveals the deeper continuous grooves and rapid removal of materials in the form of the debris, occurred as a result of more wear rate. From the worn out surfaces (Fig. 3a–d), it was observed that adhesive wear was dominant.

The surface worn-out at optimum condition (L = 10 N, V = 4 m/s, D = 2000 m, R = 12 wt-% – Fig. 4), shows very fine and shallow scratches which results in less wear rate. This was attributed to the presence of reinforcement particles at the surface which tends to bear the load that impacted on the matrix surface and delays the process of wear.

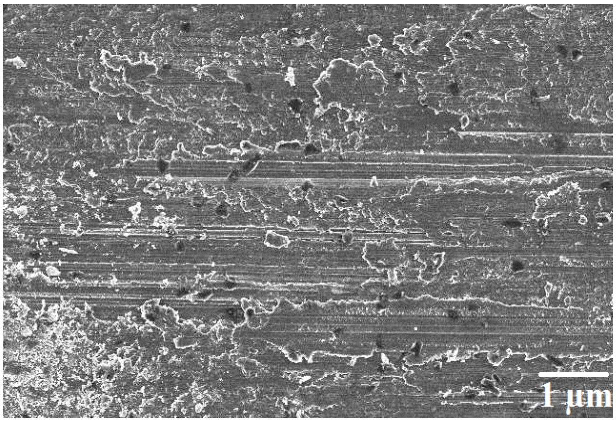

Fig 4. SEM examination of the worn-out surface at optimum condition.

5.5 Linear regression model

The parameters such as load, velocity, sliding distance and wt-% of reinforcement were correlated to the quality characteristics through the employment of regression equations in the linear form. The regression relation for the wear rate (mm^3/m) was:

$$\text{Wear rate} = 0.00464 + 0.000063\,L - 0.000556\,V - 0.000001\,D - 0.000156\,R \qquad (2)$$

Where L was the load (N), V was the velocity (m/s), D was the sliding distance (m) and R was the reinforcement (wt-%). The wear rate was estimated through the Eq. (2) by substituting the preferred new set of values (Table. 6)

Table 6. Parameter and levels selected for confirmation experiment.

S.No	Load (N)	Velocity (m/s)	Sliding distance (m)	Reinforcement (wt-%)
1	15	1.2	700	3
2	25	1.7	1200	6
3	32	2.5	1600	9
4	38	3.7	1800	11

The sign on the equation infers the trend of the wear behaviour. The positive sign prefixed parameter indicates that wear rate increases as it gets increased and negative sign indicates that, wear rate decreases as it gets increased. The same parameter levels of regression analysis (Table 6) were preferred for performing the confirmation test which infers on the efficiency of the developed statistical model. The experiments were performed for the preferred levels and the wear rate obtained from confirmation experiments were compared with the correlation results. Thus, the design process was concluded finally with confirmation experiment to validate the results brought up from the analysis. The wear rate obtained from confirmation experiment and correlation were shown in Table 7.

Table 7. Results of confirmation experiment and correlation analysis

S.No	Experimental wear rate (mm^3/m)	Regression wear rate (mm^3/m)	Error (%)
1	0.003846	0.003749	2.52
2	0.003220	0.003133	2.70
3	0.002371	0.002262	4.59
4	0.001530	0.001460	4.57

The error occupied was not more than 5 % which evident that the developed model has greater efficiency in predicting the wear behaviour of the composites.

6. CONCLUSIONS

The investigation on the wear behaviour of the composites as the function of load, velocity, sliding distance and wt-% of reinforcement using Taguchi's design of experiments was carried out successfully. The wear behaviour increases with increasing load and decreases with increasing velocity, sliding distance and wt-% of reinforcement.

The signal-to-noise ratio analysis and analysis of variance results reveals that load has the highest significance on the wear rate followed by wt-% of reinforcement, velocity and sliding distance. Hence, principal consideration should be given to load when considering the wear behaviour of the composites. The integration of B_4C reinforcement particles in the matrix decreases the wear rate of the composites thereby wear resisting capability of the composites increased with the increasing wt-% of reinforcement. The worn-out surfaces reveal the transition of mild to normal wear and normal to severe wear as the result of increase in load. The reinforcement plays a role next to load which reduces the severe wear drastically and increases the wear resistance of the composites.

The correlation and the confirmation experiments results were found to be synchronised with each other with high accuracy. Thus the incorporation of the reinforcement particles in these composites makes them feasible to use in automotive and aerospace engine wear applications which considerably improves the lifetime of the components with their high wear resistance capability.

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