

Optimization of friction and wear behaviour of Al7075-Al₂O₃-B₄C metal matrix composites using Taguchi method

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Abstract: The present study deals with investigations relating to dry sliding wear behaviour of the Al 7075 alloy, reinforced with Al₂O₃ and B₄C. The hybrid composites are produced through Liquid Metallurgy route – Stir casting method. The amount of Al₂O₃ particles is varied as 3, 6, 9, 12 and 15 wt% and the amount of B₄C is kept constant as 3wt%. Experiments were conducted based on the plan of experiments generated through Taguchi's technique. A L27 Orthogonal array was selected for analysis of the data. The investigation is to find the effect of applied load, sliding speed and sliding distance on wear rate and Coefficient of Friction (COF) of the hybrid Al7075-Al₂O₃-B₄C composite and to determine the optimal parameters for obtaining minimum wear rate. The samples were examined using scanning electronic microscopy after wear testing and analyzed.

1. Introduction

Conventional materials have certain shortcomings in good combination of strength, stiffness, toughness and density. In order to conquer these shortcomings and to meet the demand of modern day technology, composites are extensively used. Out of which, Hybrid Metal Matrix Composites (HMMCs) possess high specific strength, toughness, impact strength and low sensitivity to temperature changes [1]. As a result, many of the current applications for HMMCs are widely in the field of aerospace and automobile components. Aluminium matrix is reinforced with ceramic particles like Al₂O₃, B₄C, SiC, TiB₂, etc, which increases the mechanical properties of the resulting composite materials by dispersion strengthening mechanism. Veeresh kumar et al. [2] have reported that addition of 2 – 6 % of SiC and Al₂O₃ reinforcements to the Al6061 and Al7075 alloys respectively resulted in enhanced density, hardness, tensile strength and wear resistance for the composites. Arunkumar and Swamy [3] reinforced the Al6061 matrix with varying percentage of fly ash and e-glass fibers, and concluded that the tensile properties, compressive strength and hardness of hybrid metal matrix composite increased with increasing fly ash content. Dhanalakshmi et al. [4] have found that the increasing the reinforcement percentage in the hybrid Al7075- Al₂O₃- B₄C composite increases the tensile strength and hardness of matrix.

The most accepted method for analyzing the wear properties is dry sliding wear test. Basavarajappa et al [5] studied the dry sliding wear behaviour of the Al2219 alloy, reinforced with SiC particles in 0–15 wt. % in three steps. The results showed that the wear rates of the composites are lower than that of the



matrix alloy and further decrease with increasing SiC content. The dry sliding wear test is commonly carried out using pin-on-disc apparatus which includes various test parameters like normal load, rotational speed, time and sliding distance [6-8]. Reddy et al [9] studied the wear behaviour of hybrid metal matrix composites of Al 6061 alloy base material by incorporating 6% SiC and varying 2 to 4 % of graphite particulates. The wear resistance of the composites increases with addition of the SiC and graphite particle content. Radhika et al. [10] found Taguchi technique as a valuable technique to deal with responses influenced by multivariable. This method significantly reduces the number of trials that are required to model the response function compared with the full factorial design of experiments. The most important benefit of this technique is to find out the possible interaction between the factors. Basavarajappa et al [11] made an attempt to study the influence of wear parameters using L27 orthogonal array. Al2219 alloy was reinforced with SiC particle reinforcement varied from 0 to 15 wt% in steps of 5. Sliding distance is the wear factor that has the highest influence on the dry sliding wear of the composites followed by load, sliding speed and reinforcement on the dry sliding wear of the metal matrix composites. In the present work wear parameters have been optimized using Taguchi technique to obtain better tribological properties in the produced Al7075- Al_2O_3 - B_4C hybrid metal matrix composite and to study the influence of the wear parameters.

2. Materials and methods

The Hybrid Aluminium Metal Matrix Composites (HAMMCs) are produced through Stir casting method. Aluminium alloy 7075 is used as the matrix material and its chemical composition is shown in Table 1. Boron carbide (B_4C) and Alumina (Al_2O_3) particles are used as reinforcement. The amount of B_4C addition has been kept constant (3 wt%) and the amount of Al_2O_3 addition was varied as 3, 6, 9, 12 and 15 wt% during the stir casting process. Table 2 shows the nomenclature for the prepared HAMMCs in the present study.

Table 1. Chemical composition of Al7075 alloy.

Elements	wt%
Si	0.4
Fe	0.5
Cu	1.6
Mn	0.3
Mg	2.5
Cr	0.15
Zn	5.5
Ti	0.2
Al	bal.

Table 2. Nomenclature of different composites and the corresponding compositions.

Composite Nomenclature	Al_2O_3 (%)	B_4C (%)	Al7075 (%)
C1	3	3	94
C2	6	3	91
C3	9	3	88
C4	12	3	85
C5	15	3	82

The melt temperature is maintained above 750°C to compensate the heat loss during the pouring operation. The reinforcement materials are preheated to more than 400°C and the mold is preheated to 300°C to reduce the temperature gradient. The composites are cast into cylindrical specimens.

3. Dry sliding wear test

Pin-on-disc wear test machine was used to study the wear behavior of the samples according to ASTM G99 standard. The EN31 steel with a hardness of 62 HRC was used as the counter disc. The wear test pins having dimension of 10 mm diameter and 30 mm long is prepared from the composites and held against the rotating steel counter disc during the test. Between each tests, the counter disc and the samples are thoroughly cleaned to remove any wear debris attached to the disc or sample. The surfaces of the pin samples were rubbed against emery paper prior to test in order to ensure effective contact of the flat surface with the steel disc. The weight of the sample before and after the test is measured using digital weighing balance with high accuracy of 0.0001g after thorough cleaning with the acetone solution. The wear rate is calculated from the weight loss and expressed in terms of wear volume loss per unit sliding distance. The surface morphologies of the pins are studied using scanning electron microscope after the wear test.

Design of experiments technique enables us to carry out modeling and analysis of the influence of process variables on the response variables. The wear parameters chosen for the experiment are applied load (L), sliding speed and (S) and sliding distance (D). The process parameters and their levels are shown in table 3. Based on Taguchi method, the experiments are carried out as per the standard L27 orthogonal array. The selection of the orthogonal array is based on the condition that the degrees of freedom for the orthogonal array should be greater than or at least equals sum of those of wear parameters.

Table 3. Process parameters and their levels.

Level	Load (N)	Speed (m/s)	Distance (m)
1	20	1.5	1000
2	40	3	2000
3	60	4.5	3000

4. Plan of experiments

In the present investigation L27 orthogonal array is chosen which has 27 rows and 13 columns. The selection of Orthogonal array depends on three items in order of priority, viz., the number of factors and their interactions, number of levels for the factors and the desired experimental resolution or cost limitations. A total of 27 experiments were performed based on the run order generated by the Taguchi model. The response for the model is wear rate and coefficient of friction. In Orthogonal array, first column is assigned to applied load, second column is assigned to Sliding speed and fifth column is assigned to sliding distance and the remaining columns are assigned to their interactions. The objective of model is to minimize wear rate and coefficient of friction. The responses were tabulated and results were subjected to Analysis of Variance (ANOVA). The Signal to Noise (S/N) ratio, which condenses the multiple data points within a trial, depends on the type of characteristic being evaluated. The S/N ratio for wear rate and coefficient of friction is analyzed using 'smaller the better' characteristic. The experimental observations are further transformed into Signal to Noise ratio. The response to be studied was the wear rate and coefficient of friction with the objective as smaller the better, which is calculated as logarithmic transformation of loss function as shown below,

$$\frac{S}{N} = -10 \log\left(\frac{1}{n} \sum Y_i^2\right) \quad (1)$$

where 'n' is the number of observations, 'Y_i' is the measured value of wear rate. It is suggested that quality characteristics are optimized when the S/N response is as smaller as possible.

5. Results and discussion

The effect of the tribological test parameters such as load, sliding speed and distance on wear rate and coefficient of friction have been optimized and evaluated using Taguchi technique, with appropriate Signal-to-Noise ratio (S/N) and Analysis of Variance (ANOVA). These design parameters are unique and inherent feature of the process that influence and decide the composite performance. The parameters that highly influence the wear rate and coefficient of friction have been determined by the rank value which has been obtained from the difference between the maximum and minimum value (delta) of the mean of S/N ratios.

5.1 Results of statistical analysis of experiments

By conducting the experiment as per the Orthogonal Array, the results for various combinations of parameters were obtained. The measured results were analyzed using the commercial software MINITAB 16 specifically used in DOE applications. Table 4 shows the L27 Orthogonal array for the composite C5 that exhibited better tribological properties than other composites (C1, C2, C3 and C4), which may be due to the fact that the surface of the matrix materials tend to get delaminated in the absence of harder reinforcement, thus increasing the wear. The experimental values are transformed into a signal to noise ratio to measure the quality characteristics. The effect of control parameters such as load, sliding speed and sliding distance on wear rate and COF has been analyzed using S/N ratio response table. The ranking of process parameters using signal to noise ratios that has been obtained for various parameter levels for wear rate and COF are given in the response tables 5 and 6 respectively for composite C5. The control factors are statistically significant in the Signal to Noise ratio and it has been observed that the load is a dominant parameter on the wear rate and COF, followed by sliding speed and distance. Figure (1-4) shows the influence of process parameters on wear rate and coefficient of friction graphically. The analysis of these experimental results using S/N gives the optimum conditions resulting in minimum wear rate and coefficient of friction. The optimum condition for wear rate and coefficient of friction are L1, S3 and D3.

5.2 Analysis of Variance Results for Wear Test

The experimental results were analyzed by ANOVA, which is used to examine the influence of the wear parameters, namely, applied load, sliding speed and distance that extensively affects the performance measures. By performing ANOVA, the independent factor which dominates over the other can be determined and the percentage contribution of that particular independent variable can be found out. Tables 7 and 8 show the ANOVA results for wear rate and coefficient of friction for three factors varied at three levels and interactions of those factors. This analysis is carried out for a significance level of $\alpha = 0.05$, i.e. for a confidence level of 95%. Sources with a P-value less than 0.05 were considered to have a statistically significant contribution to the performance measures. In the Analysis of Variance tables, the last column shows the percentage contribution (Pr) of each parameter on the total variation indicating their degree of influence on the result.

Table 4. Orthogonal Array of HAMMC - C5 (15% Al₂O₃ + 3% B₄C).

Exp.No.	Load (N)	Speed (m/s)	Distance (m)	Wear rate (mm ³ /m)	S/N ratio (db)	Coefficient of friction	S/N ratio (db)
1	20	1.5	1000	0.002698	51.3792	0.319	9.9242
2	20	1.5	2000	0.002683	51.4276	0.301	10.4287
3	20	1.5	3000	0.002454	52.2025	0.293	10.6626
4	20	3.0	1000	0.002596	51.7139	0.297	10.5449
5	20	3.0	2000	0.002204	53.1358	0.290	10.7520
6	20	3.0	3000	0.001738	55.1990	0.284	10.9336

7	20	4.5	1000	0.001937	54.2574	0.288	10.8122
8	20	4.5	2000	0.001588	55.9830	0.276	11.1818
9	20	4.5	3000	0.001305	57.6878	0.274	11.2450
10	40	1.5	1000	0.003034	50.3597	0.327	9.7090
11	40	1.5	2000	0.002956	50.5859	0.319	9.9242
12	40	1.5	3000	0.002754	51.2007	0.311	10.1448
13	40	3.0	1000	0.003013	50.4200	0.319	9.9242
14	40	3.0	2000	0.002713	51.3310	0.313	10.0891
15	40	3.0	3000	0.002524	51.9582	0.295	10.6036
16	40	4.5	1000	0.002636	51.5811	0.305	10.3140
17	40	4.5	2000	0.002351	52.5749	0.294	10.6331
18	40	4.5	3000	0.002279	52.8451	0.283	10.9643
19	60	1.5	1000	0.003792	48.4226	0.346	9.2185
20	60	1.5	2000	0.003364	49.4629	0.335	9.4991
21	60	1.5	3000	0.002937	50.6419	0.318	9.9515
22	60	3.0	1000	0.003254	49.7516	0.340	9.3704
23	60	3.0	2000	0.002912	50.7162	0.327	9.7090
24	60	3.0	3000	0.002794	51.0755	0.309	10.2008
25	60	4.5	1000	0.003118	50.1225	0.323	9.8159
26	60	4.5	2000	0.002712	51.3342	0.318	9.9515
27	60	4.5	3000	0.002688	51.4114	0.286	10.8727

Table 5. Response Table for S/N Ratios – Smaller is better (Wear rate) – C5.

Level	Load (N)	Speed (m/s)	Distance (m)
1	53.67	50.63	50.89
2	51.43	51.70	51.84
3	50.33	53.09	52.69
Delta	3.34	2.46	1.80
Rank	1	2	3

Table 6. Response Table for S/N Ratios – Smaller is better (Coefficient of friction) – C5.

Level	Load (N)	Speed (m/s)	Distance (m)
1	10.721	9.940	9.959
2	10.256	10.236	10.241
3	9.843	10.643	10.620
Delta	0.877	0.703	0.661
Rank	1	2	3

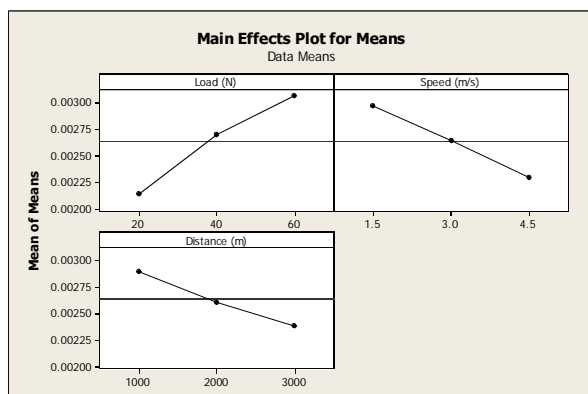


Figure 1. Main Effects plot for Means – Wear rate – C5.

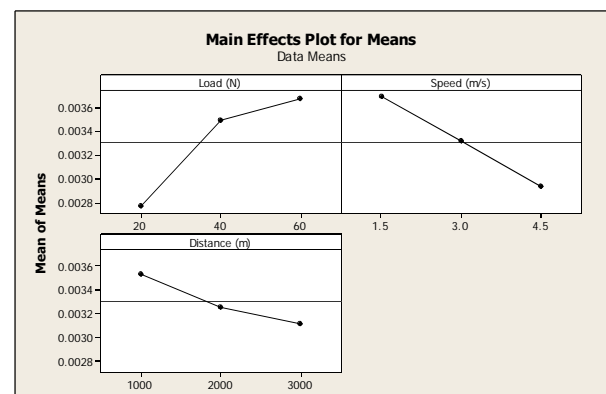


Figure 2. Main Effects plot for Means – Coefficient of friction – C5.

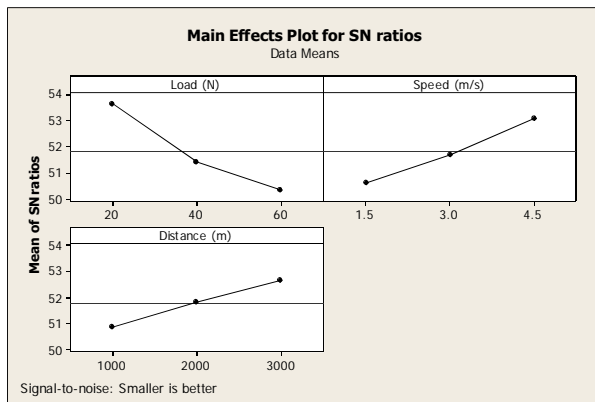


Figure 3. Main Effects plot for S/N ratio – Wear rate – C5.

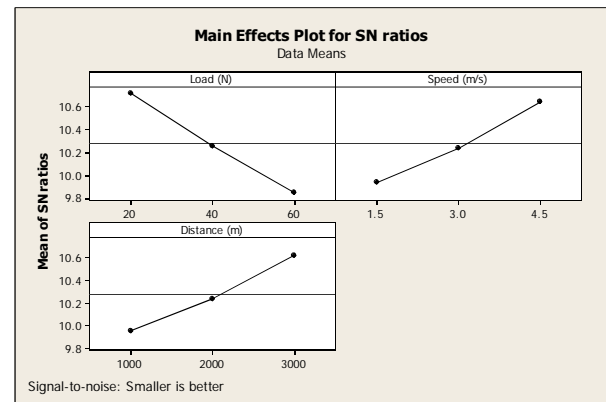


Figure 4. Main Effects plot for S/N ratio – Coefficient of friction – C5.

Table 7. Analysis of Variance for wear rate (mm^3/m) – C5.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Pr (%)
L (N)	2	0.0000039	0.0000039	0.0000020	108.19	0.000	50.64
S (m/s)	2	0.0000020	0.0000020	0.0000010	55.92	0.000	25.97
D (m)	2	0.0000012	0.0000012	0.0000006	32.47	0.000	15.58
L(N)*S(m/s)	4	0.0000003	0.0000003	0.0000001	4.00	0.045	3.89
L(N)*D(m)	4	0.0000001	0.0000001	0.0000000	0.84	0.539	1.29
S(m/s)*D(m)	4	0.0000001	0.0000001	0.0000000	0.64	0.649	1.29
Error	8	0.0000001	0.0000001	0.0000000			1.29
Total	26	0.0000077					100

Table 8. Analysis of Variance for Coefficient of friction – C5.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Pr (%)
L (N)	2	0.0043567	0.0043567	0.0021784	116.64	0.000	43.24
S (m/s)	2	0.0027570	0.0027570	0.0013785	73.81	0.000	27.36
D (m)	2	0.0024890	0.0024890	0.0012445	66.64	0.000	24.70
L(N)*S(m/s)	4	0.0000366	0.0000366	0.0000091	0.49	0.744	0.36
L(N)*D(m)	4	0.0002686	0.0002686	0.0000671	3.60	0.058	2.66
S(m/s)*D(m)	4	0.0000177	0.0000177	0.0000044	0.24	0.910	0.175
Error	8	0.0001494	0.0001494	0.0000187			1.48
Total	26	0.0100750					100

It can be observed from the Analysis of Variance results that load has the highest influence on wear rate and Coefficient of friction. Hence load is an important control factor to be taken into consideration during wear process followed by sliding speed and distance. However, the interactions between load and sliding speed, load and distance and sliding speed and distance have got negligible influences. The pooled errors associated in ANOVA table for wear rate and coefficient of friction has been approximately less than 3% for all the HAMMCs.

5.3 Multiple Linear Regression Models

Multiple Linear Regression models have been generated for wear rate and coefficient of friction using the statistical software MINITAB 16. This model gives the correlation between an independent / predictor

variable and a response variable by fitting a linear equation to observed data. The generated Regression equation thus establishes relationship between the significant terms obtained from ANOVA analysis, namely, applied load, sliding speed and sliding distance.

The Regression Equation developed for wear rate for the composite - C5 is:

$$W_r = 0.00288589 + 2.32444e-005 L - 0.00022437 S - 2.55833e-007 D$$

The Regression Equation developed for Coefficient of friction for the composite - C5 is:

$$C_f = 0.324037 + 0.000777778 L - 0.00822222 S - 1.17222e-005 D$$

From the Regression equations, it has been observed that the wear rate and coefficient of friction associated with load (L) has been positive and it indicates that, as load increases, wear rate and coefficient of friction of the composite also increases. Moreover, sliding speed and distance has been negatively associated with the equation, which indicate that, as speed and distance increases, wear rate and friction decreases. Figure 5 (a-e) shows the wear track patterns (i.e. worn surfaces) of the HAMMCs that were studied using scanning electron microscope (SEM) for the optimal parameters L1S3D3 (20N, 4.5m/s, 3000m). The presence of pits or prows is clearly observed in the worn surfaces, which is an indication of adhesive wear. As the percentage of reinforcement increases, the volume of prows also decreases.

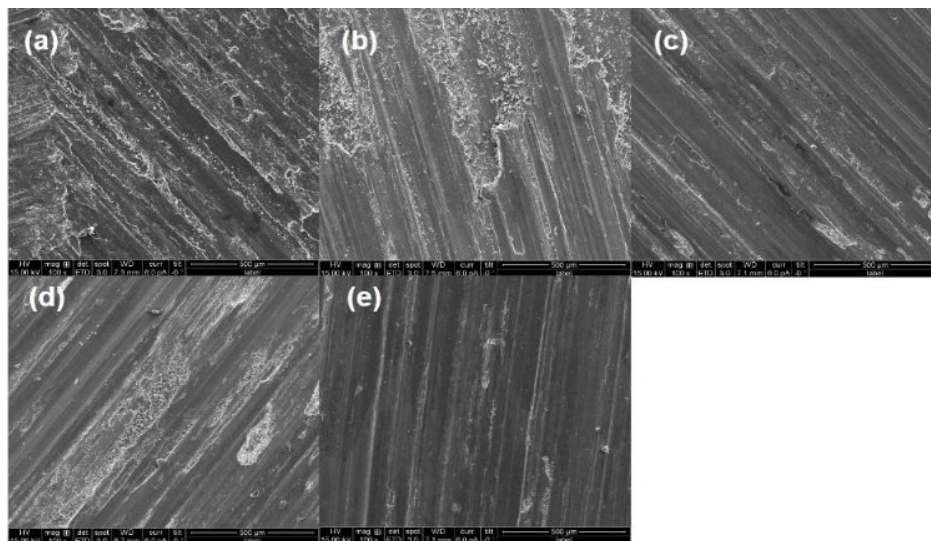


Figure 5 (a-e): SEM images of worn surface of HAMMCs C1–C5.

The effect of applied load is directly proportional to wear rate and friction, i.e., as applied load increases, wear rate and coefficient of friction also increases. This is because, the temperature at the interface between the disc and the pin increases with increase in the applied load. At low loads there is a probability of abrasive wear, where the reinforcing hard alumina particles remain undamaged without fracture during wear and thus act as load bearing elements. As the load increases, the induced stresses surpass the fracture strength of the particles causing their fracture. Thus material transfer from pin onto the disc can also occur due to the rubbing action of the fractured reinforcing particles against steel disc and the removal of material from the surface of the pin increases with increase in load.

As sliding speed increases, the wear rate and coefficient of friction decreases. This can be ascribed to the oxidation of aluminium alloy, which forms an oxide layer at higher interfacial temperature thus preventing the sliding, thereby decreasing the wear rate and coefficient of friction. The negative value of distance is indicative that increase in sliding distance decreases the wear rate as well as coefficient of friction and this can be attributed to the presence of hard reinforcing particles which provides abrasion resistance, resulting in improved dry sliding wear performance. The addition of reinforcement in the aluminium composites improves the friction and wear behaviour due to its self lubrication property. The reinforcement particles smear on the sliding pin surface and form a layer which reduces wear.

6. Conclusions

Taguchi's method is used to find the optimum conditions to achieve better wear resistance under dry sliding condition for the hybrid Al7075-Al₂O₃-B₄C composites produced through stir casting method. The following are the conclusions drawn from the present study.

- The wear resistance of the hybrid Al7075-Al₂O₃-B₄C composites increases with increasing Al₂O₃ weight percentage in the composite.
- ANOVA results show that load has the highest influence followed by sliding speed and distance, both on wear rate and coefficient of friction.
- From the Regression equations, it has been observed that load is positively associated; speed and distance are negatively associated with wear rate and coefficient of friction.

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