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Investigation to Minimize Wear Rate and Coefficient of Friction in Al6063-Sic-Al_2o_3 Hybrid Metal Matrix Composites Using Taguchi and Anova Techniques

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ABSTRACT

The present study focuses on the development and tribological [1][2][3] evaluation of Al6063T6-based hybrid metal matrix composites [3][7] (HMMCs) made strong by the coating of silicon carbide (SiC) and aluminum oxide (Al_2O_3) powder. In a crucible furnace, the metal powder is mixed when the temperature is raised. The mixing is done by the stir casting method. The experiment is done by a pin-on-disc machine with various load sliding distances and sliding speeds, and it takes out the readings on wear rate and coefficient of friction. Taguchi's [1][4][11] L9 orthogonal array was employed to optimize experimental trials, while ANOVA[4][11] linear model analysis was applied to determine the significance of control factors. Results indicated that the applied load had the most significant impact on wear rate and coefficient of friction. The multiple regression models[1][4][6] developed using MINITAB 22 software provided predictive insights into the wear performance of the composites. This demonstrates the material's suitability for high-temperature wear applications.

Keywords:
Al6063, Hybrid Metal Matrix Composites, Stir Casting, Wear Rate, Coefficient of Friction, Taguchi Method, ANOVA, SiC, Al2O3

1. INTRODUCTION:

In the last two decades, researchers have diverted their minds from parent material to composite material to meet the global demand for lightweight, high-performance, environmentally friendly, wear- and corrosion-resistant materials[4][6]. Metal Matrix Composites (MMCs) are used to make automotive industry [5] parts like brake rotors and drums, piston and cylinder liners, drive shafts, and connecting rods. In the aerospace industry[6], industrial and mechanical applications, defense[3] and military, marine and naval applications, electronics and thermal management, and construction and structural applications are done with this material.

The fabrication of MMC is a very critical and challenging one because, during fabrication time, more porosity and poor wettability are formed due to improper reinforcement. After the material is placed in a crucible furnace heated by the atmospheric air and melted, the material is melted until it reaches a specific temperature. The two-step stirring is used to mix the material thoroughly. It is also used for good reinforcement[5][8]. This method is used to build the strength, wear, and lubricating behaviors. In Al reinforced with the above 5% volume fraction of silicon carbide, the weight of the stir-casting specimen should be higher than the weight of the powder metallurgy specimen. The strength of powder metallurgy lies in improving its wear resistance.

Metal matrix composite materials making is an interesting topic that improves the properties of mechanical, physical, and chemical properties. The world is interested in improving mental characteristics like friction, wear, and lubrication by the manufacturing of hybrid metal matrix composites and making the combined properties of aluminum metal. The aluminum HMMC is reinforced with SiC and is developed through advanced foundry techniques. It is reinforced in 10% to 15% of that material weight. After the reinforcement, check the properties, density, and wear. The silicon carbide is increased as per the range; it will increase the characteristics of the matrix materials. But at the same time, the density is decreased through the increase of reinforcement. The reinforcement plays a major role in increasing the properties of the matrix material.

The matrix materials have more strength compared to the normal parent material. Composites are a stronger material compared with aluminum. Without reinforcement, the material is low in strength and wear quality; therefore, we do the reinforcing process, which will increase the stiffness, strength, and wear resistance. The higher mechanical and physical properties are used to tolerate and fulfill the many needs of engineering fields like automobiles and construction. It plays a greater role in solving wear resistance and weight loss problems. The most interesting materials commercially utilize SiC, Al_2O_3, or B_4C particles incorporated into the aluminum matrix by a variety of processes, including powder metallurgy. The processes of powder mixing are used to verify the internal properties of metal, like physical and chemical properties. In powders or pre-alloyed form, with the reinforcement in a blending process. In addition to that, in this process, a low temperature is used for fabrication when compared to the melting process; thus, it avoids chemical reactions between the matrix and reinforcement material. Another advantage of the powder metallurgy technique is its ability to manufacture sharp and accurate shape products at low cost and give good dimensional tolerance for complex geometries.

2. EXPERIMENTAL DETAILS

Al 6063-SiC-Al2O3 is taken as the investigation material to investigate the abrasive wear behavior. The conceptual procedure was followed to determine the abrasive wear rate of Al 6063-SiC-Al_2O_3. The compositions of material are listed in Table 1. All the material was available in the form of sheets from which powder was produced. The pins were made in cylindrical form with a diameter of 14 mm and a length of 55 mm. The materials were selected for disc cast iron with a thickness of 14 mm & an outer diameter of 160 mm. Various Methodologies available in this systems are below,

2.1 MATERIAL SELECTION

Although Al 6063 exhibits good tribological properties, it becomes dimensionally unstable at elevated temperatures above 120°C.

2.2 SELECTION OF MATERIAL FOR THE STUDY OF ABRASIVE WEAR

Al 6063 is a cost- and energy-effective substitute among the Al MMCs in various sliding wear applications, especially for its good tribomechanical properties [3].

2.3 COMPOSITE FABRICATION

Al 6063 reinforced with SiC and Al_2O_3[4][6] hybrid composites is fabricated by the stir casting[5][8] method and machined into the required size for wear rate calculation.

2.4 DOE AND EXPERIMENTAL WORK

The important control factor is identified. Developing the design matrix using an L9 [6] orthogonal array design and conducting experiments as per the design matrix. Take wear rate and coefficient of friction readings in pin-on-disc machine testing to know the significant characteristics of metals.

2.5 OPTIMIZATION

By using Taguchi L9 and ANOVA linear model analysis [6], we find which factor is in control and plays the major role in wear rate and coefficient of friction. The S/N ratio is calculated and shown in numerical and graphical methods. The optimum value and percentage contribution are calculated from ANOVA using MINITAB 22 software [6][11].

Al 6063	Si	Fe	Cu	Mn	Mg	Zn	Ti	Cr	Al
Weight (%)	0.5200	0.3300	0.0250	0.0810	0.5100	0.0300	0.0170	0.0160	98.5

Table 1. Material Composition Ratios

Figure 1. Pin-On-Disc set up.

. The initial weight of each pin was measured using an electronic weighing machine. In this machine, the pin is held in the specimen, and the weight is applied above the pin. The specimen surface touches the coated disc, and when the disc rotates, the surface starts to wear. The tests were conducted in loads of 30, 40, and 50, with sliding distances of 1500, 900, and 300, and sliding speeds of 100, 300, and 500. After each experiment, the pin was weighed to calculate the wear rate in terms of weight loss. In testing time, take out the reading of wear rate & COF. The levels of process parameters are shown in Table 2. The experiment was conducted as per a Taguchi L9 orthogonal array, having 3^3 rows in which the first column was assigned to load, the second column to sliding speed, and the third column to sliding distance.

Levels	Load (N)	Sliding Speed (RPM)	Sliding distance(M)
1	30	100	1500
2	40	300	900
3	50	500	300

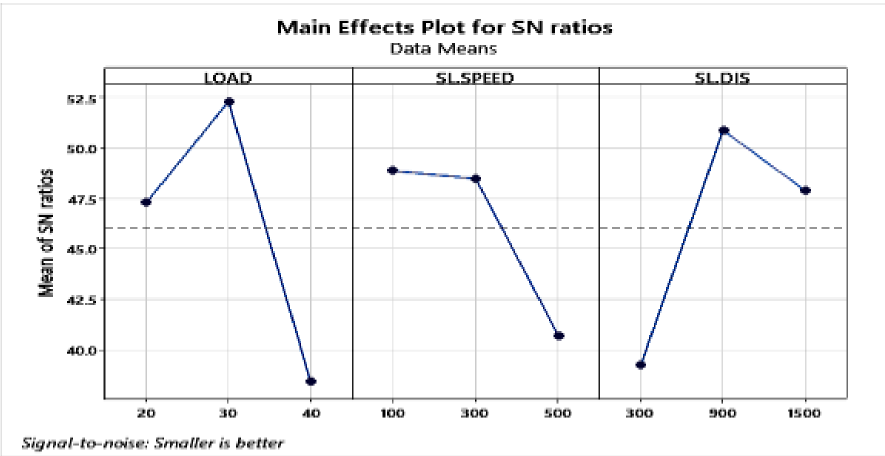
Table 2. Levels of operating parameters

3. RESULTS AND DISCUSSION

Wear rate was calculated by the sequence of the L9 orthogonal array of the Taguchi method by varying load, rotating speed, and sliding distance on the pin-on-disc apparatus. Load, sliding distance, and sliding speed are compared with wear rate and coefficient of friction, and the S/N ratio is calculated to determine the significant values. Graphing the effects and visually identifying the significant factors.

Sl. No	Load (N)	Sliding Speed (rpm)	Sliding distance (m)	Wear rate (mm^3/m)	S/N ratio (DB)	C.O. F	S/N ratio
1	30	100	1500	0.00254	51.8930728	6.854	-16.59122113
2	30	300	900	0.00211	53.51435089	6.875	-16.67186588
3	30	500	300	0.01506	36.4463848	4.986	-13.85341398
4	40	100	900	0.00086	61.33025424	6.994	-17.45710489
5	40	300	300	0.00403	47.89174404	6.737	-16.3075697
6	40	500	1500	0.00411	47.71893788	7.431	-16.88084084
7	50	100	300	0.02141	33.38604403	4.854	-12.57186512
8	50	300	1500	0.00629	44.03389436	6.308	-15.85903417
9	50	500	900	0.01284	37.82667035	5.651	-14.40484037

Table 3. Experiment data and S/N ratio for C.O. F and Wear rate



Level	LOAD	SL.SPEED	SL.DIS
1	47.28	48.87	39.24
2	52.31	48.48	50.89
3	38.42	40.66	47.88
Delta	13.9	8.21	11.65
Rank	1	3	2

(a) Wear Rate

Level	LOAD	SL.SPEED	SL.DIS
1	-15.71	-15.54	-14.24
2	-16.88	-16.28	-16.18
3	-14.28	-15.05	-16.44
Delta	2.6	1.23	2.2
Rank	1	3	2

(b) C.O. F

Fig. 2 S/N Ratio plot for a) Wear Rate b) C.O. F

The highest S/N ratio corresponds to the best quality characteristics, regardless of the category of the performance characteristics. The optimal level of the process parameter is decided by the highest S/N ratio. From the response table of the COF & main effects plot (Fig. 2), the optimum combination of design parameters is A1B3C2. The optimum combination of specific wear rates is (A1B3C2). Fig. 2 shows that the main effect plot of the S/N ratio for specific wear rate indicates that at applied load (42.70%), sliding distance (38.11%), and sliding speed (16.29%). The applied load[4][7] plays a major role and has a high influence on the S/N ratio, and plays a highly dominant role in wear behavior. Under conditions of higher load & sliding distance, the friction material is forced against the disc, resulting in higher temperature at the interface. Thereby destroying the transfer film at a faster rate, causing more wear of the friction material. In the case of COF, it is clear that at high load & minimum time, the COF decreases because the surface temperature of the friction material increases with high load & epoxy resin in the friction material is soft due to frictional heat at the interface. Thus, a reduction of COF occurs. At the maximum duration of braking, thermal loading between the pin & disc is homogeneous & uniform contact conditions on the pin and disc friction surface. This way, the COF is increased due to the pin & disc.

3.1. ANALYSIS OF VARIANCE

The analysis of variance (ANOVA) in linear model analysis was used to analyze the above results to find the wear rate and COF by the parameters of load, sliding distance, and sliding speed[6][10]. Also, knowing about the affected ratio of performance by this parameter by performing an analysis of variance, it can be decided which independent factor dominates over the other, and the percentage contribution of that particular independent variable. Tables 6 and 7 clearly define the characteristics of the above matrix metal by the three variables and three factors[6]. This analysis is carried out for a significance level of $\alpha=0.05$ 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. The percentage of contribution for COF of sliding distance, load, and sliding speed is about 42.21%, 46.41%, and 8.65% for COF. Also, the wear rates are about 38.11%, 42.70%, and 16.29%.

Table 6. ANOVA (Linear model analysis) Table for wear rate

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
LOAD	2	0.000172	42.70%	0.000172	0.000086	14.72	0.064
SL. SPEED	2	0.000065	16.29%	0.000065	0.000033	5.62	0.151
SL.DIS	2	0.000153	38.11%	0.000153	0.000077	13.14	0.071
Error	2	0.000012	2.90%	0.000012	0.000006		
Total	8	0.000402	100.00%				

Table 6. ANOVA (Linear model analysis) Table for C.O.F

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
LOAD	2	3.1688	46.41%	3.1688	1.58440	17.00	0.056
SL. SPEED	2	0.5906	8.65%	0.5906	0.29530	3.17	0.240
SL.DIS	2	2.8823	42.21%	2.8823	1.44116	15.47	0.061
Error	2	0.1864	2.73%	0.1864	0.09318		
Total	8	6.8281	100.00%				

Confirmation Test: -

A confirmation experiment is the final step in the design process.

In wet sliding conditions, the experiment is again done with the three different loads, sliding speeds, and sliding distances. The output results also compare with previous results and find out the error %, wear, and COF. After the optimal level of testing parameters had been found, verification tests needed to be carried out to evaluate the accuracy of the analysis and to validate the experimental results.

Table 7. Confirmation Experiment for Wear rate and Coefficient of friction

Exp No	Load (N)	Sliding Speed (rpm)	Sliding distance (m)
1	40	500	1500
2	50	300	1500
3	50	500	900

Table 8. Confirmation experiment results and Error%

Exp wear Rate (mm^3/m)	Reg Model wear Rate (mm^3/m)	% Error	Exp Coefficient of Friction	Reg Model Coefficient of friction	% Error
0.00411	0.004301	4.65	7.431	6.8626	7.65
0.00629	0.006573	4.50	6.308	6.6512	5.44
0.01284	0.012366	3.69	5.651	5.8762	3.99

The experimental value of the wear rate was found to vary from the wear rate calculated in the regression equation by an error percentage between 3.69% and 4.65%, while for the coefficient of friction, it was between 3.99% and 7.65%. The results of the response generated by the regression model and the results of confirmation experiments shared a good degree of closeness. Hence, the developed regression model was capable of predicting the wear rate and coefficient of friction.

4. REGRESSION ANALYSIS

A multiple linear regression model was developed using the statistical software "MINITAB 22." This model gives the relationship between an independent/predicted variable and a response variable by fitting a linear equation to observed data. The regression equation thus generated establishes a correlation between the significant terms obtained from ANOVA analysis, namely applied load, sliding speed, and sliding distance. The regression equations developed for Al 6063-SiC-Al2O3 MMCs' wear rate and coefficient of friction were as follows.:

Regression Equation (01)

Wear Rate = 0.007695 - 0.00113 (LOADx20) - 0.00469 (LOADx30) + 0.00582 (LOADx40) + 0.00058 (SL. SPEEDx100) - 0.00355(SL. SPEEDx300) + 0.00298 (SL. SPEEDx500) + 0.00581 (SL. DISx300) - 0.00242 (SL. DISx900) - 0.00338 (SL. DISx1500)

Regression Equation (02)

C.O. F = 6.299 - 0.061(LOADx20) + 0.755(LOADx30) - 0.695 (LOADx40) - 0.065 (SL. SPEED x100) + 0.341(SL. SPEEDx300) - 0.276 (SL. SPEEDx500) - 0.773 (SL. DISx300) + 0.208 (SL. DISx900) + 0.565 (SL. DISx1500)

From Eq. (1), it was observed that as the load and sliding distance increased and the sliding speed decreased, the wear rate increased. But in this condition, the coefficient of friction is reduced. In Eq. (2), sliding distance and load played a major role as well, followed by sliding speed. Overall, the reinforced Al-6063 hybrid MMC's regression equation gives a clear indication that the coefficient of friction is highly influenced by sliding distance and load.

From Eq (1) and Eq (2), clearly define the sliding distance and load; if the load is increased, the wear rate is decreased. At the same time, the coefficient of friction also increased, like this matrix material. This type of material, having an oxide layer at a higher temperature, will decrease the wear rate and coefficient of friction in aluminum matrix materials, depending on their parameters.

The negative value of distance was indicative that an increase in sliding distance decreased the wear rate as well as the coefficient of friction for both MMCs, the presence of hard SiC particles, which provide abrasion resistance, resulting in enhanced dry sliding wear performance.

5. CONCLUSION

The following conclusions were drawn from the study on wet sliding wear tests for Al 6063-SiC-Al2O3 hybrid MMCs using Taguchi's technique. The S/N ratio was used to identify the optimal combination of wet sliding wear parameters. The lowest wear rate occurred at low load[1][4], high sliding speed, and high sliding distance. The optimal levels for wear rate were A2, B1, and C2. The optimal level for the coefficient of friction was A2, B2, and C3.

The results of ANOVA revealed that the contribution of applied load (42.70%) had the greatest influence on the wear rate, followed by sliding speed (16.29%) and sliding distance (38.11%). For the coefficient of friction, the contribution of applied load (46.41%) was the largest influence on the coefficient of friction, followed by sliding distance (42.21%) and sliding speed (8.65%).

The regression equation generated for the present model was used to predict the wear rate and coefficient of friction of Al-based hybrid composites for intermediate conditions with reasonable accuracy. A confirmation experiment was carried out and made a comparison between experimental values, showing an error associated with wet sliding wear and coefficient of friction in hybrid matrix materials varying from 3.69% to 4.65% and 3.99% to 7.65%, respectively. The confirmation of the experiments and the regression model proved that the regression model was very close to the confirmation experiments.

Thus, the Taguchi method of experiment design was successfully used to predict the hybrid composite's tribological behavior. Future work can investigate dry wear behavior and microstructural analysis post-wear.

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