Optimization of Tribological Parameters in Al6061/SiC Metal Matrix Composite by Taguchi's Technique

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Abstract

Tribological behavior of aluminium alloy Al 6061 reinforced with silicon carbide (10%) fabricated by stir casting process was investigated. Dry sliding wear test was conducted to understand the tribological behavior of samples. This study is carried out to optimize the tribological properties: wear rate & frictional force of Al / SiC metal matrix composite. The experiments were conducted as the Taguchi design of experiment. A L_9 orthogonal array was selected for analysis of the data. The wear parameters chosen for the experiment were: sliding speed, applied load & sliding distance. Each parameter was assigned three levels. Signal to Noise ratio analysis has been carried out to determine optimal parametric condition, which yields minimum wear rate & frictional force. Investigation to find the influence of applied load, sliding speed and sliding distance on wear rate, as well as the frictional force during wearing process was carried out using ANOVA and regression equations for each response were developed. Objective of the model was chosen as "smaller the better" characteristics to analyze the dry sliding wear resistance. Result show that sliding distance and load have the highest influence on minimum wear rate and frictional force respectively. Finally, confirmation tests were carried out to verify the experimental results and Scanning Electron Microscopic (SEM) studies were done on the wear surfaces.

Keywords: Metal matrix composites; Silicon Carbide; Taguchi Technique; Signal to Noise

I. INTRODUCTION

In the last two decades, Researcher has shifted from monolithic materials to composite materials to meet the global demand for light weight, high performance, environmental friendly, wear & corrosion resistant materials. Particulate reinforced metal matrixes Composites have combination of low density, improved stiffness and strength, high wear resistance and isotropic properties [5]. These properties of MMCs enhance their uses in automotive and tribiological application in the field of automobile,MMCs are used for piston, Brake Drum and Cylinder block because of better corrosion and wear resistance [7,8].

The principle tribiological parameter effects the friction and wear performance of dis-continously reinforced aluminium composite are surface interaction, Mechanical characteristic (Extrinsic to materials), Material characteristic (Intrinsic to material) and tribo-contact condition. Most frequently encountered factors which are associated with four tribological parameter such as mechanical parameter, surface interaction, material parameter and tribo contact which yields wear and friction mechanism. The mechanical parameter depends upon the different factor such as loading condition, contact geometry and duration of interaction. Surface interaction parameter depends upon the various operations such as rolling, sliding, impact, erosion, fretting and reciprocating. Material parameter associated with types of chemical bonding, thermal properties, fracture toughness, hardness and yield strength. Tribo contact parameter concern with chemical reaction during dry or lubricated sliding. Dry sliding wear behavior of Al Metal Matrix Composite has been reported (and abrasive wear of Al Composites has extensively reviewed by Deuis et al [13]. Uyyuru et al [14] studied the effect of reinforcement volume fraction and size distribution of reinforced the tribological behavior of Al-Composites and Martin investigated the temperature effect on the wear behavior of particulate reinforced Al based composite[15] and influence of heat treatment on the wear behavior of Al Composites by M. A. Chowhury et al[12]. Effect of aging on behavior of MMCs was carried out by Guo et al [16] The result shows that SiC particles are effective agents in increasing dry sliding wear resistance of Al6061/SiC Composite.

Much research carried out to understand wear behavior of composite material. Meager information is available regarding the optimization of tribological parameters: Sliding wear rate and Frictional force of the metal matrix composite. In this light, this study is carried out to optimize tribological parameters of Silicon Carbide (10%) reinforced Al Metal Matrix Composite using Taguchi's Parameter design methodology.

1.1 Design of Experiment

Quality characteristic of a product under investigation in response to a factor introduced in the experimental design is the 'signal' of the desired effect. The effect of external factors (uncontrollable factor) on the outcome of quality characteristics under test is termed as 'noise'. The S/N Ratio measures the sensitivity of the quality characteristic being investigated in a controlled manner to those of external influencing factors (noise factor) not under control. The S/N Ratio is transformed figure of merit, created from the loss function. S/N Ratio combines both the parameters (the mean level of the quality and the variation around this mean) in a signal metric. The aim in any experiment is always to determine the highest possible ratio for the result (wear rate and frictional force) a high value of S/N Ratio implies the signal is much higher then the random effect of noise factor.

II. EXPERIMENTAL DETAILS

2.1 Test Materials

In the present investigation, Al 6061 was chosen as the base matrix since its properties can be tailored through heat treatment process. The reinforcement of SiC was, average size of 150 to 160 microns, and there are sufficient literatures including the improvement in wear properties through the addition of SiC. Due to the property of high hardness and high thermal conductivity, SiC after accommodation in soft ductile aluminium base matrix, enhance the wear resisting behaviour of the Al / SiC metal matrix composite.

Table 1 Chemical composition of matrix alloy Al – 6061

Chemical composition	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
%	0.4-0.8	0.7	0.15-0.40	0.15	0.8-1.2	0.04-0.35	0.25	0.2	Balance

2.2 Composite Preparation

In order to achieve high level of mechanical properties in the composite, a good interfacial bonding (wetting) between the dispersed phase and the liquid matrix has to be obtained. Stir-casting technique is one such simplest and cost effective method to fabricate metal matrix composites which has been adopted by many researchers. This method is most economical to fabricate composites with discontinuous fibres and particulates and was used in this work to obtain as the cast specimens. Care was taken to maintain an optimum casting parameter of pouring temperature (650℃) and stirring time (15 min). The reinforcements were preheated prior to their addition in the aluminium alloy melt. Degassing agent (hexachloro ethane) was used to reduce gas porosities. The molten metal was then poured into a permanent cast iron mould of diameter 26mm and length 300mm. The die was released after 6 hours and the cast specimens were taken out.

2.3 Wear Behaviour

The aim of the experimental plan is to find the important factors and combination of factors influencing the wear process to achieve the minimum wear rate and frictional force. The experiments were developed based on an orthogonal array, with the aim of relating the influence of sliding speed, applied load and sliding distance. These design parameters are distinct and intrinsic feature of the process that influence and determine the composite performance [17]. Taguchi recommends analysing the S/N ratio using conceptual approach that involves graphing the effects and visually identifying the significant factors.

2.4 Plan of experiment using orthogonal array

Dry sliding wear test was performed with three parameters: applied load, sliding speed, and sliding distance and varying them for three levels. According to the rule that degree of freedom for an orthogonal array should be greater than or equal to sum of those wear parameters, a L_9 Orthogonal array which has 9 rows and 3 columns was selected.

Table 2 Process parameters and levels

Level	Load (N)	Sliding Speed (m/s)	Sliding Distance(m)
1	10	2	1000
2	20	3	1750
3	30	4	2500

2.5 Experimental Procedure

To evaluate the tribological performance of the composites under dry sliding condition, wear tests were carried out on a pin on disc type friction and wear monitoring test rig. Specimens of size 10 mm diameter and 25 mm length were cut from the cast samples, and then machined. The contact surface of the cast sample (pin) was made flat so that it should be in contact with the rotating disk. During the test, the pin was held pressed against a rotating EN31 carbon steel disc (hardness of 65HRC) by applying load that acts as counterweight and balances the pin. The track diameter was varied for each batch of experiments in the range of 50 mm to 100 mm and the parameters such as the load, sliding speed and sliding distance were varied in the range given in Table 2. A LVDT (load cell) on the lever arm helps determine the wear at any point of time by monitoring the movement of the arm. Once the surface in contact wears out, the load pushes the arm to remain in contact with the disc. This movement of the arm generates a signal which is used to determine the maximum wear and the coefficient of friction is monitored continuously as wear occurs and graphs between co-efficient of friction and time was monitored for the specimens i.e., 10 % SiC/ Al-6061 MMCs.

Table 3 Results of L_9 Orthogonal array for Al – 6061 / 10% SiC MMC

S. No.	L (N)	S (m/s)	D (m)	Frictional Force (FF) N	Wear rate (mm^3/m)	S/N ratio (FF) db	S/N ratio (wear rate) db
1	10	2	1000	3.11	0.00481	-9.8552	46.3571
2	10	3	1750	2.90	0.0036	-9.2779	48.8739
3	10	4	2500	2.77	0.00178	-8.8496	54.9916
4	20	2	1750	7	0.00422	-16.902	47.4938
5	20	3	2500	6.86	0.00222	-16.7265	53.0729
6	20	4	1000	7.44	0.0037	-17.4315	48.6360
7	30	2	2500	10.8	0.00296	-20.6685	50.5742
8	30	3	1000	12.3	0.0037	-21.7981	48.6360
9	30	4	1750	11.7	0.00254	-21.3637	51.9033

III. RESULT DISCUSSION

3.1 Signal to Noise Ratio

The experimental observations are transformed into Signal to Noise ratio. There are several S/N ratios available depending on the type of characteristics under study. The wear rate & frictional force are coming 'smaller is better' type of quality characteristic and the respective S/N ratio is calculated using formula given below.

$$S/N = -10 log \frac{1}{n} \sum_{i=1}^{n} y_i^2$$

Where n = no. of tests in a trial

For the present study n = 2

The aim of this experiment is to determine the highest possible Signal to Noise ratio for the parameters under study. A high value of S/N ratio implies that signal is much higher than the random effects of noise factors. The S/N ratio was computed using above formula for each response of the Table 3.

3.2 Results of Statistical Analysis of Experiments

The results for various combinations of parameters were obtained by conducting the experiment as per the orthogonal array. The measured results were analysed using the commercial software MINITAB 15 specifically used for design of experiment applications [23]. Table 3 shows the experimental results average of two repetitions for wear rate and frictional force. To measure the quality characteristics, the experimental values are transformed into signal to noise ratio. The influence of control parameters such as load, sliding speed, and sliding distance on wear rate and frictional force has been analysed using signal to noise response table. The ranking of process parameters using signal to noise ratios obtained for different parameter levels for wear rate & frictional force are given in Table 3 and Table 4 for 10% reinforced SiC MMCs. The control factors are statistically significant in the signal to noise ratio and it could be observed that the sliding distance is a dominant parameter on the wear rate and frictional force followed by applied load significantly. Figure 1 to Figure 4 shows for 10% influence of process parameters on wear rate and coefficient of friction graphically. The analysis of these experimental results using S/N ratios gives the optimum conditions resulting in minimum wear rate and coefficient of friction. The optimum condition for wear rate and frictional force as shown in Table 8.

3.3 Analysis of Variance Results for Wear Test

The experimental results were analysed with Analysis of Variance (ANOVA) which is used to investigate the influence of the considered wear parameters namely, applied load, sliding speed, and sliding distance that significantly affect the performance measures. By performing analysis of variance, it can be decided which independent factor dominates over the other and the percentage contribution of that particular independent variable. Table 6 and Table 7 shows 10% SiC MMCs of 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 •=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.

Table 4 Response Table for Signal to Noise Ratios Smaller is better (Wear Rate)

Level	Load	Speed	Distance
1	50.07	48.14	47.88
2	49.73	50.19	49.42
3	50.37	51.84	52.88
Delta	0.64	3.70	5.00
Rank	3	2	1

Table 5 Response Table for Signal to Noise Ratios Smaller is better (friction force)

Level	Load	Speed	Distance
1	-9.328	-15.809	-16.362
2	-17.020	-15.934	-15.848
3	-21.277	-15.882	-15.415
Delta	11.949	0.126	0.947
Rank	1	3	2

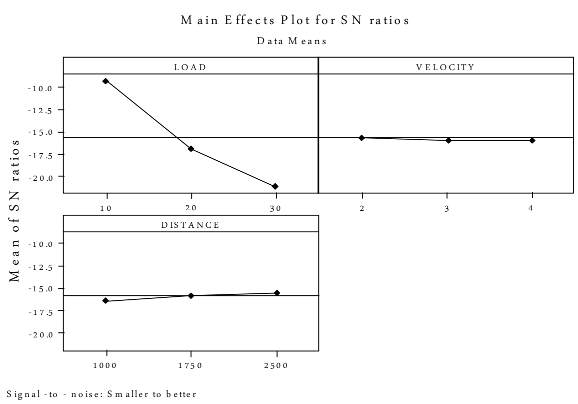

Fig.1 Main effects plot for S/N ratios –Frictional force

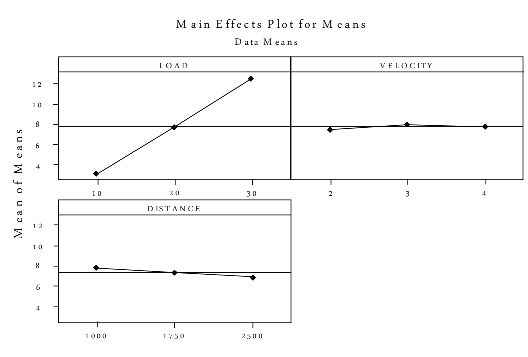

Fig.2 Main effects plot for Means –Frictional force

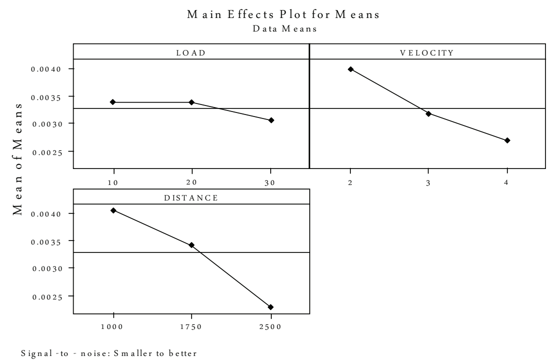

Fig.3 Main effects plot for Means –Wear Rate

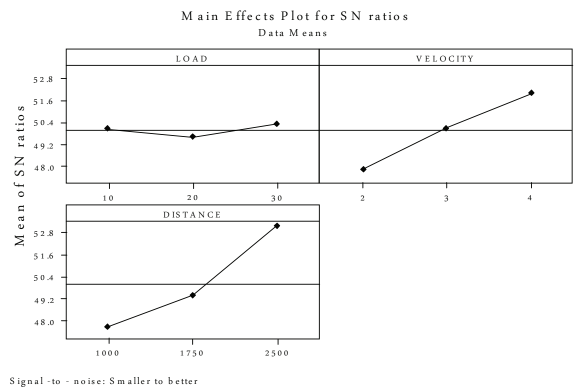

Fig.4 Main effects plot for S/N ratios –Wear Rate

Table 6 Analysis of Variance for Means (Wear Rate)

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Pr(%)
Load	2	0.6095	0.6095	0.3047	0.28	0.783	0.970228
Speed	2	20.6381	20.6381	10.3190	9.37	0.096	32.8526
Distance	2	39.3697	39.3697	19.6849	17.87	0.053	62.67035
Error	2	2.2031	2.2031	1.1015			3.506987
Total	8	62.8203					100

Table 7 Analysis of Variance for Means (Frictional force)

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Pr(%)
Load	2	220.077	220.077	110.039	3896.40	0.000	99.35532
Speed	2	0.024	0.024	0.012	0.42	0.703	0.010835
Distance	2	1.348	1.348	0.674	23.86	0.040	0.608564
Residual Error	2	0.056	0.056	0.028			0.025282
Total	8	221.505					100

It can be observed that for aluminium 10% SiC Metal Matrix Composites, from the Table 6,that the sliding distance has the highest influence (Pr =62.5%) on wear rate. Hence sliding distance is an important control factor to be taken into consideration during wear process followed by applied loads (P=0.99%) & sliding speed (Pr=32.85%) respectively. The pooled error is very low accounting for only 3.5%. In the same way from the Table 7 for frictional force, it can observe that the load has the highest contribution of about 99.35%, followed by sliding distance (0.6%) & sliding speed (0.01%) for Al-6061 with 10% SiC metal matrix composites means that negligible effect of rest both parameters. The interaction terms have little or no effect on wear rate & frictional force & the pooled errors accounts only 3.5% & 0.025%. From the analysis of variance & S/N ratio, it is inferred that the sliding distance and applied load have the highest contribution on wear rate & frictional force respectively.

IV. MULTIPLE LINEAR REGRESSION MODEL

A multiple linear regression model is developed using statistical software "MINITAB 15". This model gives the relationship between an independent / predicted variable & a response variable by fitting a linear equation to observe data. Regression equation thus generated establishes correlation between the significant terms obtained from ANOVA analysis namely applied load, sliding speed & sliding distance.

The regression equation developed for Al-6061 / (10%) SiC MMCs wear rate (Wr) and frictional force (FF) are as follows

$$Wr = 0.00764 - 0.000016\ L - 0.000662\ S - 0.000001\ D \quad \text{Eq (1)}$$

$$FF = - 1.02 + 0.433\ L + 0.167S - 0.000538\ D \quad \text{Eq (2)}$$

From Eq (1), it is observed that the applied load, sliding speed & sliding distance increases or decreases at any parametric value, it will be decrease the wear rate of the value of 0.00764mm^3/m. But in case of frictional force Eq (2), applied load plays a major role as well as followed by sliding speed and sliding distance. Overall for the 10% reinforced SiC in Al-6061 MMCs regression equation gives the clear indication about frictional force is highly influenced by applied load. Following are the observation of optimum level process parameter for wear rate and frictional force.

Table 8 Optimum level Process Parameters for Wear Rate and Frictional Force

Sr. No.	Load(N)	Sliding Speed (m/s)	Sliding Distance (m)	Wear Rate (mm^3/m)	Frictional force (N)	S/N Ratio (db)
1	30	3	1000	0.0037		48.6360
2	10	2	1750		3.11	49.9788

From Eq (1), observed that the negative value of coefficient of speed reveals that increase in sliding speed decreases the wear rate of 10% reinforced SiC MMCs. This can be attributed to the oxidation of aluminium alloy Al – 6061 which forms an oxide layer at higher interfacial temperature thus preventing the sliding, thereby decreases the wear rate & frictional force which is represented in Eq (2) and a similar behaviour has been observed [17].

From Eq (2), it is observed that the positive value of coefficient of applied load & sliding speed reveals that increase in applied load & sliding speed increases the wear rate and frictional force of 10% reinforced SiC metal matrix composites. This can be related to the reinforcement of weight percentage of silicon carbide in Al – 6061 MMCs from 10% resulted the hard & tough property of the material. Wear rate & Frictional force are largely governed by the interaction of two sliding surfaces.

To understand the wear mechanism of composites for 10% SiC, the worn surfaces were examined by Scanning Electron Microscope. During sliding, the entire surface of the pin has contact with the surface of the steel disc & machine marks can also be observed. Fig: 5 shows the microstructure of the worn surfaces of composites (for 10% SiC) at an applied load 30 N, sliding distance of 1000 m for sliding speed of 2 m/s, 3 m/s and 4 m/s respectively. Grooves were mainly formed by the reinforcing particles of SiC. As the sliding speed increases, the number of grooves also increases & the reinforcements are projecting out from the surface due to ploughing action counterface & pin and formation of wear debris was also observed in 10% SiC reinforced Al-6061 MMCs.

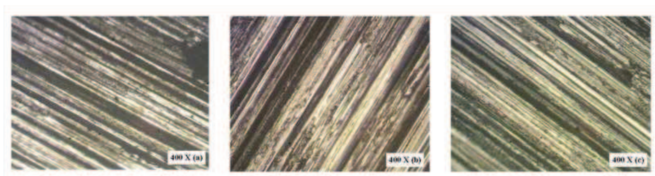

Fig 5: (a) 30 N, 2 m/s, 2500 m Fig 5: (b) 30 N, 3 m/s, 2500 m Fig 5: (c) 30 N, 4 m/s, 2500 m

The negative value of distance is indicative that increase in sliding distance decreases the wear rate as well as frictional force for both MMCs, the presence of hard SiC particle which provides abrasion resistance, resulting in enhanced dry sliding wear performance.

V. CONFIRMATION TEST

A confirmation experiment is the final step in the Design process. A dry sliding wear test was conducted using a specific combination of the parameters & levels to validate the statistical analysis.

After the optimal level of testing parameters have been found, it is necessary that verification tests are carried out in order to evaluate the accuracy of the analysis & to validate the experimental results.

Table 11 Confirmation Experiment for Wear Rate and Coefficient of Friction

MMCs	Exp. No.	Load(N)	Sliding Speed(m/s)	Sliding Distance(m)
Al-6061+10% SiC	1	13	2.4	1200
	2	19	2.8	1800
	3	28	3.5	2200

Table 12 Result of Confirmation Experiment and their comparison with Regression

MMCs	Exp. Wear Rate(mm^3/m)	Reg. Model Eq(1), Wear Rate(mm^3/m)	% Error	Exp. Frictional Force (N)	Reg. Model Eq(2), Frictional Force (N)	% Error
Al6061 +10% SiC	0.005	0.00464	7.89	4.1415	4.3642	5.11
	0.00389	0.00368	5.7	6.1413	6.7062	8.125
	0.00308	0.00277	11.23	10.1593	10.5049	3.29

The experimental value of wear rate is found to be varying from wear rate calculated in regression equation by error percentage between 5.7% to 11.23%, while for frictional force it is between 3.29% to 8.125% for 10% weight percentage of SiC reinforced with Al-6061 MMCs.

6. Conclusions

Following are the conclusions drawn from the study on dry sliding wear test using Taguchi's technique.

- Sliding distance (62.67%) has the highest influence on wear rate followed by sliding speed(32.85%) and applied load (0.97%) and for frictional force, the contribution of applied load is 99.36%, sliding distance is 0.608% for **Al – 6061/ 10% SiC** metal matrix composites.
- From the above conclusion we predict that sliding distance & applied load have the highest influence on wear rate & frictional force in composites.
- Regression equation generated for the (10% SiC MMCs) present model was used to predict the wear rate & frictional force of Al – 6061/(10%) SiC MMCs for intermediate conditions with reasonable accuracy.
- Confirmation experiment was carried out & made a comparison between experimental values showing an error associated with dry sliding wear rate & frictional force in composites varying from 5.7% to 11.23%, and 3.29% to 8.125% respectively. Thus design of experiments by Taguchi method was successfully used to optimize the parameter for tribological behavior of composites.

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