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# Tribological Behaviour of Al-6061 / SiC Metal Matrix Composite by Taguchi's Techniques

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***Abstract*****-** Tribological behaviour of aluminium alloy Al-6061 reinforced with silicon carbide particles (10% & 15%weight percentage of SiCp) fabricated by stir casting process was investigated. The wear and frictional properties of the metal matrix composites was studied by performing dry sliding wear test using a pin-on-disc wear tester. Experiments were conducted based on the plan of experiments generated through Taguchi's technique. A L9 Orthogonal array was selected for analysis of the data. Investigation to find the influence of applied load, sliding speed and sliding distance on wear rate, as well as the coefficient of friction during wearing process was carried out using ANOVA and regression equation for each response were developed for both 10% & 15% SiC reinforced Al-6061MMCs. Objective of the model was chosen as 'smaller the better' characteristics to analyse the dry sliding wear resistance. Results show that sliding distance has the highest influence followed by load and sliding speed. Finally, confirmation tests were carried out to verify the experimental results & Scanning Electron Microscope were done on wear surfaces.

***Index Terms*****-** Metal Matrix Composites, Stir casting, Taguchi's techniques, Orthogonal array, Analysis of variance, wear behaviour

## I. INTRODUCTION

In the last two decades, research has shifted from monolithic materials to composite materials to meet the global demand for light weight, high performance, environmental friendly, wear and corrosion resistant materials. Metal Matrix Composites (MMCs) are suitable for applications requiring combined strength, thermal conductivity, damping properties and low coefficient of thermal expansion with lower density. These properties of MMCs enhance their usage in automotive and tribological applications [5]. In the field of automobile, MMCs are used for pistons, brake drum and cylinder block because of better corrosion resistance and wear resistance [7,8].

Fabrication of MMCs has several challenges like porosity formation, poor wettability and improper distribution of reinforcement. Achieving uniform distribution of reinforcement is the foremost important work. A new technique of fabricating cast Aluminium matrix composite has been proposed to improve the wettability between alloy and reinforcement. In this, all the materials are placed in graphite crucible and heated in an inert atmosphere until the matrix alloy is melted and followed by two step stirring action to obtain uniform distribution of reinforcement [2]. The fabrication techniques of MMCs play a major role in the improvement of mechanical and tribological properties. The performance characteristics of Al alloy reinforced with 5% volume fraction of SiC fabricated through stir casting and found that the stir casting specimen have higher strength compared to powder metallurgy specimen. The size and type of reinforcement also has a significant role in determining the mechanical and tribological properties of the composites. The effect of type of reinforcements such as SiC whisker, alumina fiber and SiC particle fabricated by Powder Metallurgy on the properties of MMCs has been investigated. It was found that there existed a strong dependence on the kind of reinforcement and its volume fraction. The results revealed that particulate reinforcement is most beneficial for improving the wear resistance of MMCs.

There is a growing interest worldwide in manufacturing hybrid metal matrix composites [HMMCs] which possesses combined properties of its reinforcements and exhibit improved physical, mechanical and tribological properties. Aluminium matrix composites reinforced silicon carbide was developed using conventional foundry techniques. The reinforcements were varied by 10% and 15% by weight. The composite was tested for density, mechanical properties, and dry sliding wear. The results show an increasing trend in all the properties with increase in SiC content, except density which decreased with increase in reinforcements .The tribological properties of MMCs are also increased by increasing reinforcements at all applied conditions[13].

## II. DESIGN OF EXPERIMENTS (DOE)

Design of Experiment is one of the important and powerful statistical techniques to study the effect of multiple variables simultaneously and involves a series of steps which must follow a certain sequence for the experiment to yield an improved understanding of process performance [19]. All designed experiments require a certain number of combinations of factors and levels be tested in order to observe the results of those test conditions. Taguchi approach relies on the assignment of factors in specific orthogonal arrays to determine those test combinations. The DOE process is made up of three main phases: the planning phase, the conducting phase, and the analysis phase. A major step in the DOE process is the determination of the combination of factors and levels which will provide the desired information [21].

Analysis of the experimental results uses a signal to noise ratio to aid in the determination of the best process designs. This technique has been successfully used by researchers in the study of dry sliding wear behaviour of composites. These methods focus on improving the design of manufacturing processes. In the present work, a plan order for performing the experiments was generated by Taguchi method using orthogonal arrays [20]. This method yields the rank of various parameters with the level of significance of influence of a factor or the interaction of factors on a particular output response.

## III. MATERIAL SELECTION

In the present investigation, Al-SiC alloy was chosen as the base matrix since its properties can be tailored through heat treatment process. The reinforcement was sic, average size of 150 to 160 microns, and there are sufficient literatures elucidating 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 |

### 3.1 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 the as cast specimens. Care was taken to maintain an optimum casting parameter of pouring temperature (650°C) 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.

### 3.2 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 coefficient of friction. 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.

The above mentioned pin on disc test apparatus was used to determine the sliding wear characteristics of the composite. 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 both of the specimens i.e., 10 % and 15% SiC/ Al-6061 MMCs.

Further, weight loss of each specimen was obtained by weighing the specimen before and after the experiment by a single pan electronic weighing machine with an accuracy of 0.0001g after thorough cleaning with acetone solution.

The results for various combinations of parameters were obtained by conducting the experiment as per the Orthogonal array and show the Table 3. The measured results were analysed using the commercial software MINITAB 15 specifically used for design of experiment applications. Table 4 & Table 5 shows the experimental results average of two repetitions for wear rate and coefficient of friction.

**Table 2 Process parameters and levels**

| Level | Load (N) | Sliding speed, S (m/s) | Sliding distance, D (m) |
|---|---|---|---|
| 1 | 10 | 2 | 1000 |
| 2 | 20 | 3 | 1750 |
| 3 | 30 | 4 | 2500 |

## IV. PLAN OF EXPERIMENTS

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 as shown below:

**Table 3 Orthogonal array $L_9$ of Taguchi**

| Experiment No. | Column 1 | Column 2 | Column 3 |
|---|---|---|---|
| 1 | 1 | 1 | 1 |
| 2 | 1 | 2 | 2 |
| 3 | 1 | 3 | 3 |
| 4 | 2 | 1 | 2 |
| 5 | 2 | 2 | 3 |
| 6 | 2 | 3 | 1 |
| 7 | 3 | 1 | 3 |
| 8 | 3 | 2 | 1 |
| 9 | 3 | 3 | 2 |

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 9 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 third 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 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 characteristics can be divided into three categories, viz. ‘nominal is the best’, ‘larger the better’ and ‘smaller the better ‘characteristics. In this study, ‘smaller the better’ characteristics was chosen to analyse the dry sliding wear resistance. The S/N ratio for wear rate and coefficient of friction using ‘smaller the better’ characteristic given by Taguchi, is as follows:

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

Where $y_1$, $y_2$...$y_n$ are the response of friction and sliding wear and n is the number of observations. The response table for signal to noise ratios show the average of selected characteristics for each level of the factor. This table includes the ranks based on the delta statistics, which compares the relative value of the effects. S/N ratio is a response which consolidates repetitions and the effect of noise levels into one data point. Analysis of varience of the S/N ratio is performed to identify the statistically significant parameters.

## V. RESULTS AND DISCUSSIONS

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 coefficient of friction. 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. Taguchi recommends analysing the S/N ratio using conceptual approach that involves graphing the effects and visually identifying the significant factors.

### 5.1 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 4 & Table 5 shows the experimental results average of two repetitions for wear rate and coefficient of friction. 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 coefficient of friction 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 and coefficient of friction are given in Table (4.1-4.2) and Table (5.1-5.2) respectively for 10% &15% 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 coefficient of friction followed by applied load and sliding speed. Figure (4.1 - 4.4) shows for 10% influence of process parameters on wear rate and coefficient of friction graphically and Figure (5.1 - 5.4) shows for 15% influence of process parameters on wear rate and coefficient of friction graphically. The analysis of these experimental results using S/Nratios gives the optimum conditions resulting in minimum wear rate and coefficient of friction. The optimum condition for wear rate and coefficient of friction as shown in Table 10.

### 5.2 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&7) and Table (8&9) shows 10% &15% 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 α=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 Results of L9 Orthogonal array for Al – 6061 / 10% SiC MMC**

| S. No. | L (N) | S (m/s) | D (m) | Coefficient of friction | Wear rate ($mm^3/m$) | S/N ratio c.o.f | S/N ratio wear rate |
|---|---|---|---|---|---|---|---|
| 1 | 10 | 2 | 1000 | 0.311 | 0.00481 | 10.1448 | 46.3571 |
| 2 | 10 | 3 | 1750 | 0.291 | 0.0036 | 10.7221 | 48.87395 |
| 3 | 10 | 4 | 2500 | 0.277 | 0.00178 | 11.1504 | 54.9916 |
| 4 | 20 | 2 | 1750 | 0.35 | 0.00422 | 9.1186 | 47.49375 |
| 5 | 20 | 3 | 2500 | 0.343 | 0.00222 | 9.2941 | 53.07294 |
| 6 | 20 | 4 | 1000 | 0.372 | 0.0037 | 8.5891 | 48.63597 |
| 7 | 30 | 2 | 2500 | 0.36 | 0.00296 | 8.8739 | 50.57417 |
| 8 | 30 | 3 | 1000 | 0.41 | 0.0037 | 7.7443 | 48.63597 |
| 9 | 30 | 4 | 1750 | 0.39 | 0.00254 | 8.1787 | 51.90333 |

**Table 4.1 Responses table for S/N ratio for wear (10% SiC)**

| Level | Load | Sliding velocity | Sliding distance |
|---|---|---|---|
| 1 | 50.07 | 48.14 | 47.88 |
| 2 | 49.73 | 50.19 | 49.42 |
| 3 | 50.37 | 51.84 | 52.88 |
| Delta(Δ) | 0.64 | 3.70 | 5.00 |
| Rank | 3 | 2 | 1 |

**Table 4.2: Responses table for S/N ratio of coefficient of friction (10% SiC)**

| Level | load(A) | Sliding velocity(B) | Sliding distance(C) |
|---|---|---|---|
| 1 | 10.672 | 9.379 | 8.826 |
| 2 | 9.001 | 9.254 | 9.340 |
| 3 | 8.266 | 9.306 | 9.773 |
| Delta(Δ) | 2.407 | 0.126 | 0.947 |
| Rank | 1 | 3 | 2 |

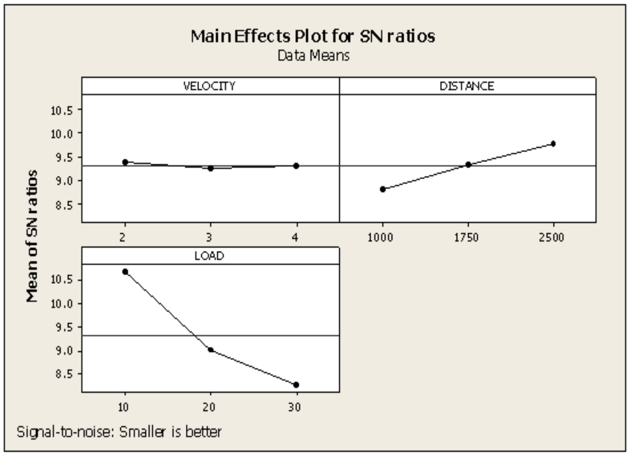


**Fig.4.1 Main effects for plot for S/N Ratios –Coefficient of Friction**

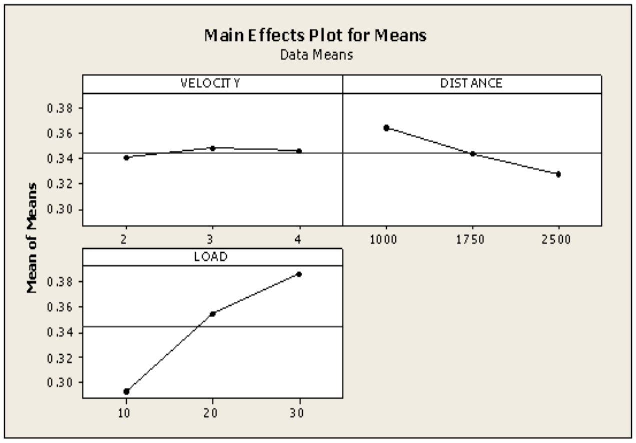


**Fig.4.2 Main effects for plot for Means –Coefficient of Friction**

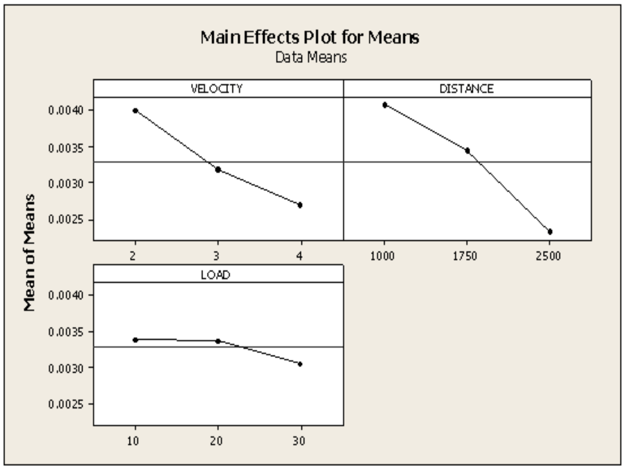


**Fig.4.3 Main effects for plot for Means –Wear Rate**

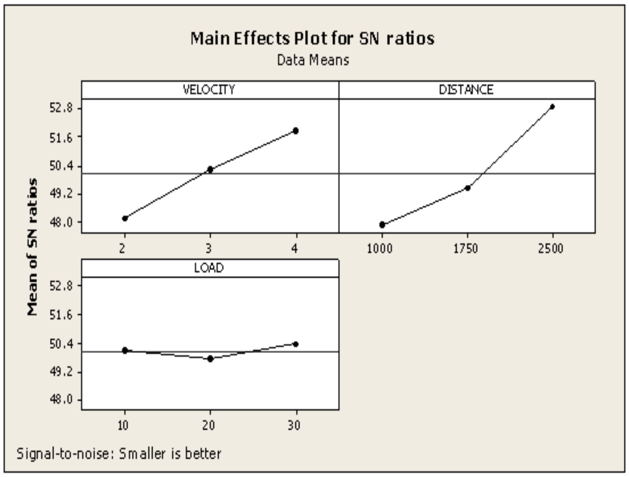


**Fig.4.4 Main effects for plot for S/N Ratio –Wear Rate**

**Table 5: Results of L9 Orthogonal array for Al – 6061 / 15% SiC MMC**

| S. No. | Load (N) | sliding velocity (m/s) | sliding distance(m) | Wear ($mm^3/m$) | Coefficient of friction | S/N Ratio (wear)(db) | S/N Ratio (cof) (db) |
|---|---|---|---|---|---|---|---|
| 1 | 10 | 2 | 1000 | 0.0037 | 0.356 | 48.6360 | 8.9710 |
| 2 | 10 | 3 | 1750 | 0.00317 | 0.33 | 49.9788 | 9.6297 |
| 3 | 10 | 4 | 2500 | 0.00593 | 0.29 | 44.5389 | 10.7520 |
| 4 | 20 | 2 | 1750 | 0.00402 | 0.426 | 47.9155 | 7.4118 |
| 5 | 20 | 3 | 2500 | 0.00252 | 0.404 | 51.9720 | 7.8724 |
| 6 | 20 | 4 | 1000 | 0.00259 | 0.455 | 51.7340 | 6.8398 |
| 7 | 30 | 2 | 2500 | 0.00207 | 0.37 | 53.6806 | 8.6360 |
| 8 | 30 | 3 | 1000 | 0.002185 | 0.41 | 53.1211 | 7.7443 |
| 9 | 30 | 4 | 1750 | 0.00169 | 0.39 | 55.4423 | 8.1787 |

**Table 5.1: Response Table for Signal to Noise Ratios (Coefficient of friction) Smaller is better**

| Level | Load | Speed | Distance |
|---|---|---|---|
| 1 | 9.784 | 7.410 | 6.430 |
| 2 | 7.375 | 6.994 | 6.995 |
| 3 | 4.424 | 7.179 | 8.158 |
| Delta | 5.360 | 0.417 | 1.728 |
| Rank | 1 | 3 | 2 |

**Table 5.2: Response Table for Signal to Noise Ratios Smaller is better (Wear Rate)**

| Level | Load | Speed | Distance |
|---|---|---|---|
| 1 | 47.72 | 50.08 | 51.19 |
| 2 | 50.54 | 51.72 | 51.11 |
| 3 | 54.11 | 50.57 | 50.06 |
| Delta | 6.39 | 1.64 | 1.13 |
| Rank | 1 | 2 | 3 |

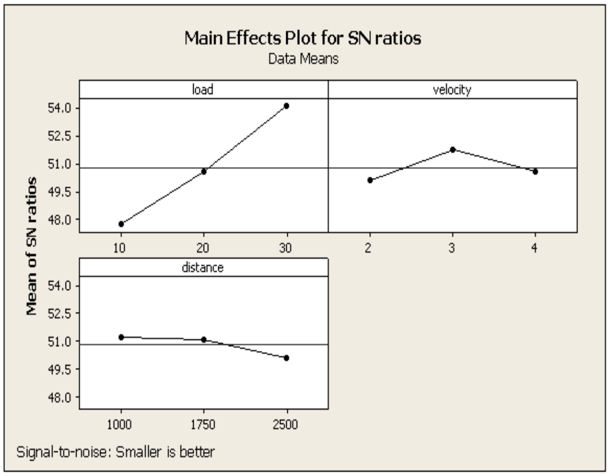


**Fig 5.1: Main effects plot for S/N ratios – Wear Rate**

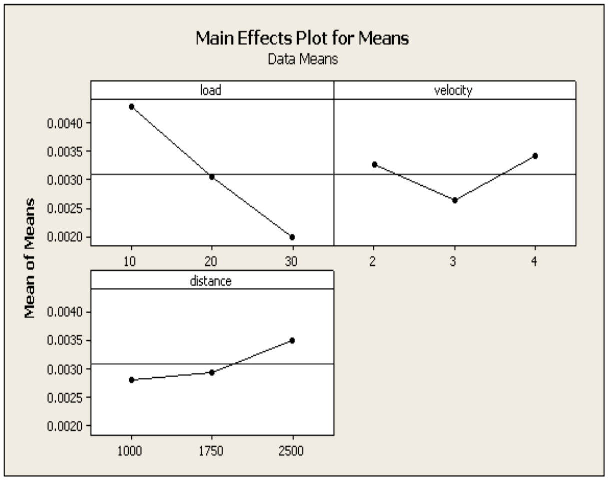
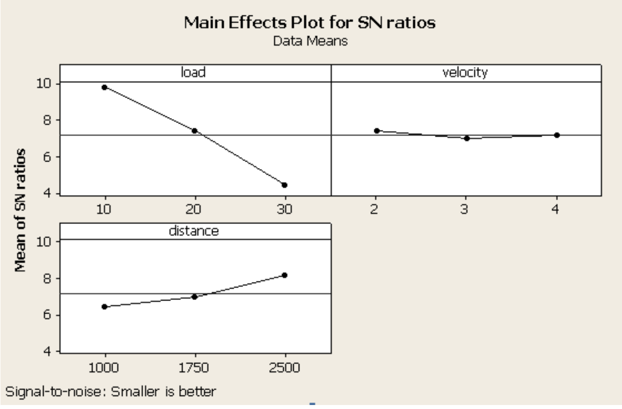


**Fig 5.2: Main effects plot for Means – Wear Rate**

**Fig 5.3: Main effects plot for S/N ratio – Coefficient of Friction**



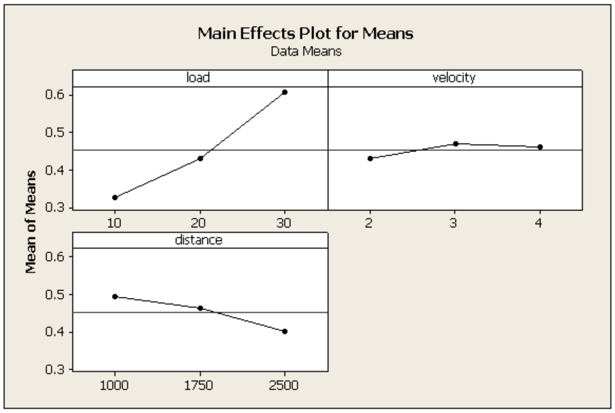


**Fig 5.4: Main effects plot for Means – Coefficient of Friction**

**Table 6:Analysis of Variance for Means (Wear Rate) (10% SiC)**

| Source | DF | Seq SS | Adj SS | Adj MS | F | P | Pr (%) |
|---|---|---|---|---|---|---|---|
| Load | 2 | 0.0000001 | 0.000000 | 0.000000 | 2.31 | 0.302 | 1.25 |
| Speed | 2 | 0.000003 | 0.000003 | 0.000001 | 29.89 | 0.032 | 37.5 |
| Distance | 2 | 0.000005 | 0.000005 | 0.000002 | 52.75 | 0.019 | 62.5 |
| Error | 2 | 0.000000 | 0.000000 | 0.000000 |  |  | 1.25 |
| Total | 8 | 0.000008 |  |  |  |  | 100.0 |

**Table 7: Analysis of Variance for Means (Coefficient of Friction) (10% SiC)**

| Source | DF | Seq SS | Adj SS | Adj MS | F | P | Pr (%) |
|---|---|---|---|---|---|---|---|
| Load | 2 | 0.013620 | 0.013620 | 0.006810 | 178.69 | 0.006 | 85.5 |
| Speed | 2 | 0.000098 | 0.000098 | 0.000049 | 1.28 | 0.439 | 0.6 |
| Distance | 2 | 0.002135 | 0.002135 | 0.001067 | 28.01 | 0.034 | 13.4 |
| Error | 2 | 0.000076 | 0.000076 | 0.000000 |  |  | 0.5 |
| Total | 8 | 0.015929 |  |  |  |  | 100.0 |

**Table 8: Analysis of Variance for Means (Coefficient of Friction) (15% SiC)**

| Source | DF | Seq SS | Adj SS | Adj MS | F | P | Pr (%) |
|---|---|---|---|---|---|---|---|
| Load | 2 | 0.120034 | 0.0120034 | 0.060017 | 58.83 | 0.017 | 87.2 |
| Speed | 2 | 0.002318 | 0.002318 | 0.001159 | 1.14 | 0.468 | 1.7 |
| Distance | 2 | 0.013311 | 0.013311 | 0.006655 | 6.54 | 0.133 | 9.7 |
| Error | 2 | 0.002040 | 0.002040 | 0.001020 |  |  | 1.4 |
| Total | 8 | 0.137703 |  |  |  |  | 100.0 |

**Table 9: Analysis of Variance for Means (Wear Rate) (15% SiC)**

| Source | DF | Seq SS | Adj SS | Adj MS | F | P | Pr (%) |
|---|---|---|---|---|---|---|---|
| Load | 2 | 0.000008 | 0.000008 | 0.000004 | 1.94 | 0.340 | 57.20 |
| Speed | 2 | 0.000001 | 0.000001 | 0.000001 | 0.26 | 0.797 | 7.10 |
| Distance | 2 | 0.000001 | 0.000001 | 0.0000005 | 0.19 | 0.838 | 7.10 |
| Error | 2 | 0.000004 | 0.000004 | 0.000002 |  |  | 28.60 |
| Total | 8 | 0.000014 |  |  |  |  | 100.0 |

It can be observed that for aluminium (10% & 15%) SiC Metal Matrix Composites, from the Table 6 & 9, that the sliding distance has the highest influence (Pr =62.5% & Pr=7.1%) on wear rate. Hence sliding distance is an important control factor to be taken into consideration during wear process followed by applied loads (P=1.25% & P=57.2%) & sliding speed (Pr=37.5% & Pr=7.1%) respectively. In the same way from the Table 7 & Table 8 for coefficient of friction, it can observe that the load has the highest contribution of about 85.5% & 87.2%, followed by sliding distance (13.4% & 9.7%) & sliding speed (0.6% & 1.7%) for Al-6061 with (10% & 15%) SiC metal matrix composites.

The interaction terms has little or no effect on coefficient of friction & the pooled errors accounts only 0.5% & 1.4%. From the analysis of variance & S/N ratio, it is inferred that the sliding distance has the highest contribution on wear rate & coefficient of friction followed by load & sliding speed.

## VI. 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 / (10%) SiC MMCs wear rate and coefficient of friction are as follows

$$Wr = 0.00764 - 0.000016\ L - 0.000662\ S - 0.000001\ D \qquad \text{Eq(1)}$$
$$C_f = 0.286 + 0.00468\ L + 0.00300\ S - 0.000025\ D \qquad \text{Eq(2)}$$

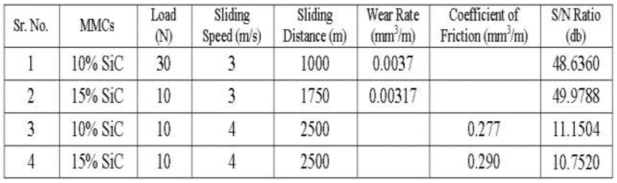
Similarly, regression equation for Al / (15%) SiC MMCs wear rate and coefficient of friction are as follows

$$Wr = 0.00438 - 0.000114L + 0.00007S + 0.0000001\ D \qquad \text{Eq (3)}$$
$$C_f = 0.237 + 0.014L + 0.0147S - 0.000062\ D \qquad \text{Eq (4)}$$

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

From Eq (3) & Eq (4), it is observed that the sliding speed plays a major role on wear rate as well as coefficient of friction. Eq (4) is highly influenced by load & sliding speed means that if load & sliding speed increases it also increase the coefficient of friction,sliding distance minutely affect the wear rate & coefficient of friction for 15% reinforcement of SiC in Al-6061 MMCs.

**Table 10: Optimum level Process Parameters for Wear Rate and Coefficient of Friction**



| Sr. No. | MMCs | Load (N) | Sliding Speed (m/s) | Sliding Distance (m) | Wear Rate ($mm^3/m$) | Coefficient of Friction ($mm^3/m$) | S/N Ratio (db) |
|---|---|---|---|---|---|---|---|
| 1 | 10% SiC | 30 | 3 | 1000 | 0.0037 | | 48.6360 |
| 2 | 15% SiC | 10 | 3 | 1750 | 0.00317 | | 49.9788 |
| 3 | 10% SiC | 10 | 4 | 2500 | | 0.277 | 11.1504 |
| 4 | 15% SiC | 10 | 4 | 2500 | | 0.290 | 10.7520 |

From Eq (1) & Eq (2),observed that the negative value of coefficient of speed reveals that increase in sliding speed decreases the wear rate & coefficient of friction 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 & coefficient of friction and a similar behaviour has been observed [].

From Eq (3) & Eq (4), it is observed that the positive value of coefficient of speed reveals that increase in sliding speed increases the wear rate & coefficient of friction of 15% reinforced SiC metal matrix composites. This can be related to the reinforcement of weight percentage of silicon carbide in Al – 6061 MMCs from 10% to 15% , resulted the brittlement property of the material. Wear rate are largely governed by the interaction of two sliding surfaces.

To understand the wear mechanism of composites for 10% &15% 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: 6 & Fig: 7 shows the microstructure of the worn surfaces of composites (for 10% & 15% SiC) at an applied load 30 N, sliding distance of 2500 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. In fig: 6 & 7 shows that more grooves in 15% SiC MMCs. 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 15% SiC reinforced Al-6061 MMCs.

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

From the observation of Eq(1), Eq(2), Eq(3) & Eq(4), we are taking a case of unit value of load, sliding speed & sliding distance, after that we get the value of wear rate and coefficient of friction as follows: For 10% SiC reinforced MMCs $W_r$ = $0.006961 mm^3/m$, $C_f$ = 0.2937 For 15% reinforced MMCs $W_r$ = $0.0043361 mm^3/m$, $C_f$ = 0.26564 due to increase in weight percentage (10% to 15%) of SiC reinforced in Al-6061 metal matrix composites, it increase the hardness of the MMCs that reveal it reduces the wear rate & coefficient of friction.

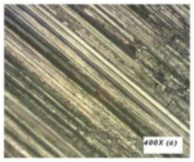


Fig 6: (a) 30 N, 2 m/s, 2500 m

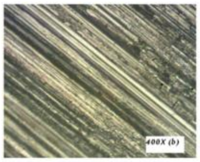


Fig 6: (b) 30 N, 3 m/s, 2500 m

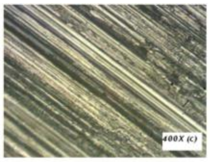


Fig 6: (c) 30 N, 4 m/s, 2500 m

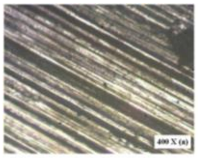


Fig 7: (a) 30 N, 2 m/s, 2500 m

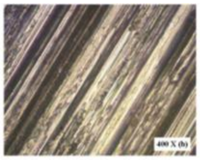


Fig 7: (b) 30 N, 3 m/s, 2500 m

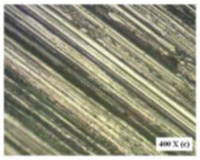


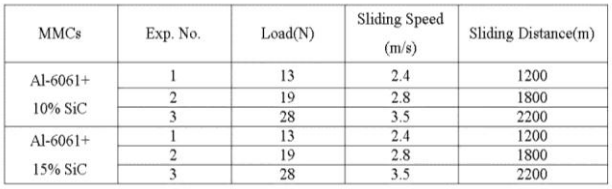
Fig 7: (c) 30 N, 4 m/s, 2500 m

## VII. 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.

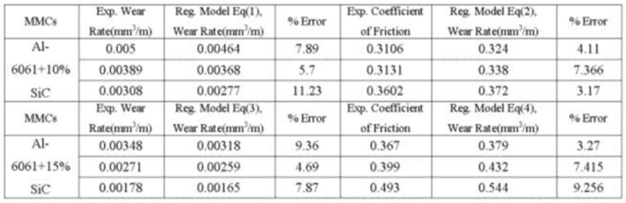
After the optimal level of testing parameters have been found, it is necessary that verification tests are carried out in order to evaluate the accuracy of the analysis & to validate the experimental results.

**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 |
| Al-6061+ 15% 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. Coefficient of Friction | Reg. Model Eq(2), Wear Rate($mm^3/m$) | % Error |
|---|---|---|---|---|---|---|
| Al-6061+10% SiC | 0.005 | 0.00464 | 7.89 | 0.3106 | 0.324 | 4.11 |
| | 0.00389 | 0.00368 | 5.7 | 0.3131 | 0.338 | 7.366 |
| | 0.00308 | 0.00277 | 11.23 | 0.3602 | 0.372 | 3.17 |
| MMCs | Exp. Wear Rate($mm^3/m$) | Reg. Model Eq(3), Wear Rate($mm^3/m$) | % Error | Exp. Coefficient of Friction | Reg. Model Eq(4), Wear Rate($mm^3/m$) | % Error |
| Al-6061+15% SiC | 0.00348 | 0.00318 | 9.36 | 0.367 | 0.379 | 3.27 |
| | 0.00271 | 0.00259 | 4.69 | 0.399 | 0.432 | 7.415 |
| | 0.00178 | 0.00165 | 7.87 | 0.493 | 0.544 | 9.256 |

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 coefficient of friction it is between 3.17% to 7.366% for 10% weight percentage of SiC reinforced with Al-6061 MMCs. But in case of 15% weight percentage of SiC reinforced with Al-6061MMCs gives the experimental value of wear rate is found to be varying from wear ratecalculated in regression equation by error percentage between 4.69% to 9.36%,while for coefficient of friction it is between 3.27% to 9.256%.

## VIII. CONCLUSIONS

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

- Sliding distance (62.5%) has the highest influence on wear rate followed by sliding speed(37.5%) and applied load (1.25%) and for coefficient of friction, the contribution of applied load is 85.5%, sliding distance is 13.4% for **Al – 6061/ 10% SiC** metal matrix composites.
- Applied load (57.2%) has the highest influence on wear rate followed by sliding distance (7.1%) and sliding speed (7.1%) and for coefficient of friction, the contribution of applied load is 87.2%, sliding distance is 9.7% for **Al – 6061/ 15% SiC** metal matrix composites.
- Increasing incorporation of SiC (10% & 15%) increases the wear resistance of composites by forming a protective layer between pin & counterface.
- From the above conclusion we predict that sliding distance & applied load have the highest influence on wear rate in both composites.
- Similarly applied load is only parameter which is largely influence the coefficient of friction in both composites.
- Regression equation generated for the (10% & 15% SiC MMCs) present model was used to predict the wear rate & coefficient of friction of Al – 6061/(10% & 15%) 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 & coefficient of friction in both composites varying from 4.69% to 11.23% and 3.17% to 9.256% respectively. Thus design of experiments by Taguchi method was successfully used to predict the tribological behavior of composites.

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