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STUDY OF WEAR BEHAVIOUR OF Al/ (Al_2O_{3P} and SiC_P) HYBRID METAL MATRIX COMPOSITES

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ABSTRACT In this study, dry sliding wear behaviour of Aluminium Hybrid Metal Matrix Composite was investigated and a prediction model was developed using Taguchi's method. Aluminium A356alloy reinforced with equal weight percentage of alumina and silicon carbide particles (10wt%, 20wt% and 30wt %) was produced using liquid metallurgy method. Experiments were conducted using Pin-on-disc tester. The sliding distance was kept constant and the effect of load, sliding velocity and weight percentage of reinforcement on the wear properties was evaluated. It was found that as load increases, wear rate also increases and it decreases as sliding velocity increases. By increasing weight percentage of reinforcements, the wear resistance increases and was found that 30% reinforced composite had less wear rate. The prediction model showed that the major parameter that influences the wear rate was load followed by weight percentage of reinforcement and sliding velocity. By confirmation test, the predicted wear rates were found to be close to the experimental values. Based on this approach, it was found that the improvement in the wear resistance of hybrid composites became more significant at high sliding velocity, low load and with high weight percentage of reinforcements.

Keywords: Dry sliding wear, Metal Matrix Composite, Alumina, Silicon carbide, Prediction model, Taguchi's method

INTRODUCTION

Nowadays cast iron made vehicle components has been replaced by weight less, wear resistant and high temperature withstanding Metal Matrix Composites (MMCs) (Erica et al, 2008). It has a metal matrix reinforced with strong ceramic reinforcement to combine the metallic properties of the matrix alloys (toughness and ductility) and the ceramic properties of the reinforcements (high modulus and high strength), leading to greater strength in compression and shear even at higher temperature, wear resistance, specific stiffness, high elastic modulus and high corrosion resistance (Hanumanth et al, 1993 and Murphy and Sahin, 1996). The composites can be manufactured by adding different types and forms of reinforcement. The particle-reinforced composites are more widely used, which can be manufactured by using melt processing-liquid-phase processing or by powder metallurgy-solid-phase processing (Kang and Seo, 1995 and Kainer et al, 1991)

Aluminium alloy, a light weight material is used in the automotive and aircraft industries for improving the vehicle efficiency by reducing its weight. Aluminium is soft, but by adding hard ceramics such as Alumina (Al_2O_3) and Silicon Carbide (SiC) particle, its structure can be made harder (Celik et al,2002 and BekirSadik Unlu,2008). The application of aluminium alloy matrix reinforced with Al_2O_3 or SiC had further increased as aluminium MMCs have shown significant improvement in tribological properties as they have good wear resistance, high load carrying capacity and light weight. (Clegg et al, 1985, Radhika et al, 2012 and Sahin, 2003)

Wear is one of the most commonly encountered industrial problems leading to the replacement of components and assemblies in engineering. By increasing the weight % of SiC reinforcement alone makes the component increase in wear resistance but difficult to machine and also SiC particles detached from composite itself acts as an abrasive. So to obtain better wear properties, other reinforcements can be added along with it. It is inferred that hardness increased as weight % of SiC increased as it has high hardness compared to aluminium. The wear rate of the composites increased as load and sliding distance increased (Rathika et al,2012).From Kok (2006) study of the wear resistance of Al/Al_2O_3, it is observed that the wear resistance of the composites increased with increasing Al_2O_3 particle content and size. But wear resistance decreased with increasing the abrasive grit size and sliding distance. The wear resistance in larger size particles is mainly due to the hardness of the reinforced particles and in smaller size particles are due to both strengthening for the matrix and the hardness of the particles.

Rodriguez et al, (2007) analysed the dry sliding wear behaviour of aluminium-lithium alloys reinforced with SiC particles and observed that the presence of mechanically mixed layers on the wear surface with varying morphology and thickness influenced the wear rate. Veeresh Kumar et al, (2010) studied the mechanical and tribological properties of Al6061-SiC and Al7075-Al_2O_3 metal matrix composites and the results concluded that Al6061-SiC exhibits superior mechanical and tribological properties. Sudarshan and Surappa (2008) discussed the dry sliding wear of fly ash particle reinforced A356 Al composites and found that the wear resistance of A356 Al alloy reinforced with narrow size range fly ash particles were superior to that of the composite having the same volume fraction of particles in the wide size range.

Based on the above literatures, to improve the wear resistance of Aluminium alloy A356, the reinforcements selected are Al_2O_3 and SiC of particle size 10 to 15μm. Three different composite samples were prepared viz., Al/5% Al_2O_3/5%SiC, Al/10% Al_2O_3/10%SiC, Al/15% Al_2O_3/15%SiC to study the adhesive wear behaviour.

In this study, dry sliding wear behaviour of the composite was tested after planning the experiment so that the data obtained can give an optimum condition where wear is least. A plan of experiments was done by Design of Experiments (DOE) which was based on Taguchi technique. An orthogonal array and Analysis of Variance was employed to investigate the influence of wear parameters such as load, sliding velocity and reinforcement percentage on dry sliding wear.

By using Analysis of Variance (ANOVA), the percentage of individual and combined influence of the design parameter over the dry sliding wear can be identified (Basavarajapa et al, 2007).

Optimization

The Design of Experiments (DOE) is an efficient procedure for planning experiments so that the data obtained can be analysed to yield valid and objective conclusions. Taguchi Method is an approach to experimental design which uses fractional factorial design. Taguchi method is one of the most efficient tools which can be used to reduce the number of variations in parameters through robust design of experiments. The independent variables (parameters) used in the study were load, sliding velocity and wt% reinforcement. The sliding distance was kept constant throughout the experiments. The parameters and its three levels are shown in Table 1.

The fractional factorial design reduces the orthogonal array to 27 rows and 3 columns. The relation between the parameters and various other relations were found out using MINITAB16 software which is specifically used for Design of Experiment application. The experimental data was converted to S/N (Signal to noise) ratio. S/N ratio is defined as the ratio of mean of the signal to standard deviation of the noise. With this, the extent of desired output is calculated and is used to analyse the rank of the input process parameters. There are three types of quality characteristics, namely larger the better, smaller the better and nominal the best. For wear rate, smaller the better was used, because wear for any application considered being low and are preferred for automotive applications.
Smaller the better characteristics $S/N = -10 \log [1/n (\sum y^2)]$ where, y is the wear rate and n is the number of observations.

With this relation, minimum wear rate is found with the available process parameter. The relative effect of one parameter over the other was found using Analysis of Variance (ANOVA) method. It is a statistical hypothesis testing used in the analysis of experimental data. It compares the mean square of the result with deviation from sample mean. The optimized result should give minimum wear rate.

Table 1. Parameters and its Levels

Parameters	Level 1	Level 2	Level 3
Load(N)	10	20	30
Velocity(m/s)	1	2	3
wt% Reinforcement	10	20	30

Experimental procedure

The specimen was fabricated using stir casting technique, machining was done based on ASTM standard and wear test was carried out using pin-on-disc wear tester. Aluminium LM25 was chosen as the base matrix and it has the density of 2.68 gm/cm^3. Alumina and silicon carbide were taken as the reinforcements and their densities were 3.95 gm/cm^3 and 3.21 gm/cm^3 respectively. Chemical composition of LM 25 alloy is given in Table 2.Synthesis of composites and dry sliding wear test is explained in detail in the following sub-headings.

Table 2. Chemical Composition of LM 25 alloy

Composition %	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Sn	Ti	Pb	Ca	Al
LM 25 Alloy	6.5 to 7.5 %	0.5 max	0.1 max	0.3 max	0.2 to 0.6	0.05 max	0.1 max	0.1 max	0.05 max	0.2 max	0.1 max	0.05 max	Remainder

Fabrication of composites

The composite specimens were fabricated by stir casting method.The stir casting technique is commonly used for fabrication of composites as this allows for uniform distribution of reinforcement in the matrix. The base metal is A356 alloy and was melted at 700ºC in a crucible. Simultaneously reinforcement was preheated to a temperature of 300ºC to improve the wettability, remove moisture and also to reduce the temperature gradient between molten metal and reinforcements. Magnesium of 2 wt% is added to the molten metal to enhance the wettability between reinforcements and molten metal. The molten metal was stirred using stirrer and measured quantity of reinforcement was added. The mixture was stirred for 5 minutes for uniform distribution. Then molten metal was poured in a sand mould and allowed to solidify. The same procedure was repeated for fabrication of composites with different weight percentage of reinforcement.

Wear test

Dry sliding wear tests for different specimens were conducted in pin on disc tester of DUCOM make (Figure1).

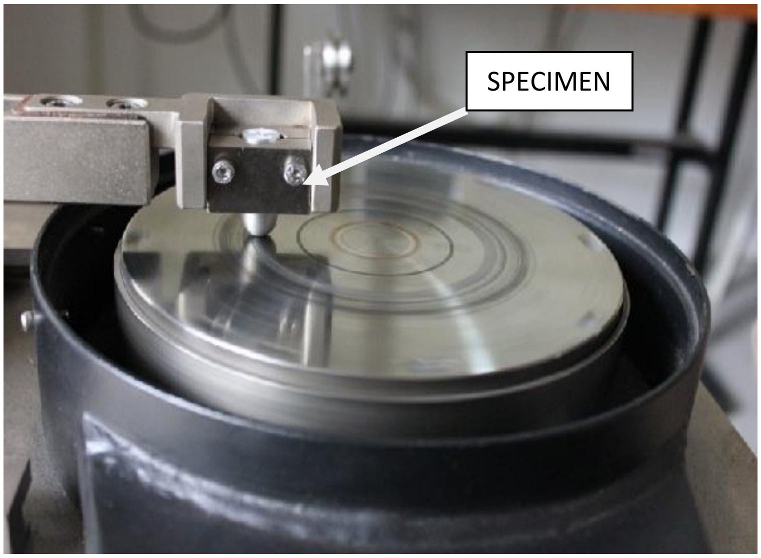


Figure 1. Wear Test Experimental Setup

The test specimens are A356 alloy with 10% reinforcements, 20% reinforcements, and 30% reinforcements (equal weight percentage of both alumina and silicon carbide). The specimens for wear
test were prepared based on ASTM standard. The diameter of pin specimen prepared was 12 mm. The sliding distance was taken constant as 1500 m and the variable parameters were load of 10,20, 30 N, sliding velocity of 1,2,3 m/s and % reinforcement of 10,20,30 % .

From the sliding velocity, the rpm of disc is calculated using the formula:

Rotating speed of disc (rpm) $=\frac{60\times\text{sliding velocity}}{\pi\times\text{track diameter}}$

where, sliding velocity in m/s and track diameter in meters(m).

The rotation time of disc is set and is calculated by using sliding distance.

Rotating time (seconds) = $\frac{\text{Distance}}{\text{Velocity}}$

where, distance in meters(m) and sliding velocity in m/s.

The surfaces of pin samples are prepared using an emery paper prior to test in order to ensure smooth surface contact with steel disc before start of each experiment. Also, the wear track was cleaned with an emery paper and then with acetone in order to remove the specimen traces which is adhered to disc track. Before the start of experiment, the pin was weighed and it was held in the specimen holder against the counter face rotating disc (steel disc) with wear track diameter of 80mm. The pin was loaded against the disc through dead weights on the lever. The load cell on this lever arm helps determine the wear at any point of time by monitoring the movement of the arm. When disc is rotated, the load cell which is connected to the computer receives the signal and the friction force is recorded. Now the wear disc is allowed to rotate at a calculated rpm and time according to velocity. After each experiment, the weight was measured and the loss of weight was calculated. The same procedure was repeated for all the experiments and wear rate was calculated for each pin using formula,

Wear rate (mm^3/m) = $\frac{\delta m}{\rho\times d}$

whereδm is difference in mass, ρ is density of the material and d is sliding distance.

RESULTS AND DISCUSSION

The wear rate for all 27 combinations, were tabulated (Table 3).

Table 3. Experimental Results for L27 Orthogonal Array

Experiment No.	Load(N)	Sliding Velocity(m/s)	% Reinforcement	Wear Rate(mm^3/m)	S/N Ratio
1	10	1	10	0.000649	63.7544
2	10	1	20	0.00043	67.3222
3	10	1	30	0.000202	73.8745
4	10	2	10	0.000672	63.4496
5	10	2	20	0.000495	66.1109
6	10	2	30	0.000407	67.8187
7	10	3	10	0.000585	64.6599
8	10	3	20	0.000383	68.3453
9	10	3	30	0.000325	69.7750
10	20	1	10	0.001439	56.8358
11	20	1	20	0.001411	57.0106
12	20	1	30	0.001113	59.0728
13	20	2	10	0.001746	55.1612
14	20	2	20	0.001664	55.5748
15	20	2	30	0.000603	64.3981
16	20	3	10	0.001028	59.7583
17	20	3	20	0.000834	61.5716
18	20	3	30	0.00045	66.9388
19	30	1	10	0.002822	50.9900
20	30	1	20	0.002712	51.3339
21	30	1	30	0.001912	54.3710
22	30	2	10	0.002587	51.7454
23	30	2	20	0.002176	53.2469
24	30	2	30	0.001368	57.2806
25	30	3	10	0.002272	52.8731
26	30	3	20	0.0009	60.9182
27	30	3	30	0.000306	70.2835

Note: S/N ratio –Signal to Noise ratio

Influence of Each Parameter onthe Wear Rate

For each level of individual parameter, average of all the wear rate values was taken. These values are shown in Table 4. For each parameter, the difference between the maximum and minimum average valve was calculated (Delta). The greater the Delta value, greater is the influence of that parameter on wear rate of the composite. For each parameter, wear rate corresponding to the level of parameters were plotted and is shown in Figure 2. Similar calculations were done using S/N Ratio. Table 5 gives the response of S/N ratio and Figure 3 shows the S/N ratio plot.

Table 4. Response Table for Means

Level	Load, L	Sliding velocity, S	%Reinforcement, R
1	0.000461	0.001410	0.001533
2	0.001143	0.001302	0.001223
3	0.001895	0.000787	0.000743
Delta	0.001434	0.000623	0.000791
Rank	1	3	2

Figure 2 shows that as load increases from 10 N to 30N, wear rate increases according to the Archard's law. This is due to increase in the area of contact at the micro-level which in turn increases the friction and temperature at the contact. Load is the most dominating factor controlling the wear behavior (Das et al, 1998).The wear rate decreases with increase in volume fraction of the reinforcement and the same trend is observed (Radhika et al,2012). This is due to increase in the hardness of the reinforcements (both silicon carbide and alumina) and also due to increase in contact area of silicon carbide and alumina. The hard reinforcements help the composites to carry more loads.

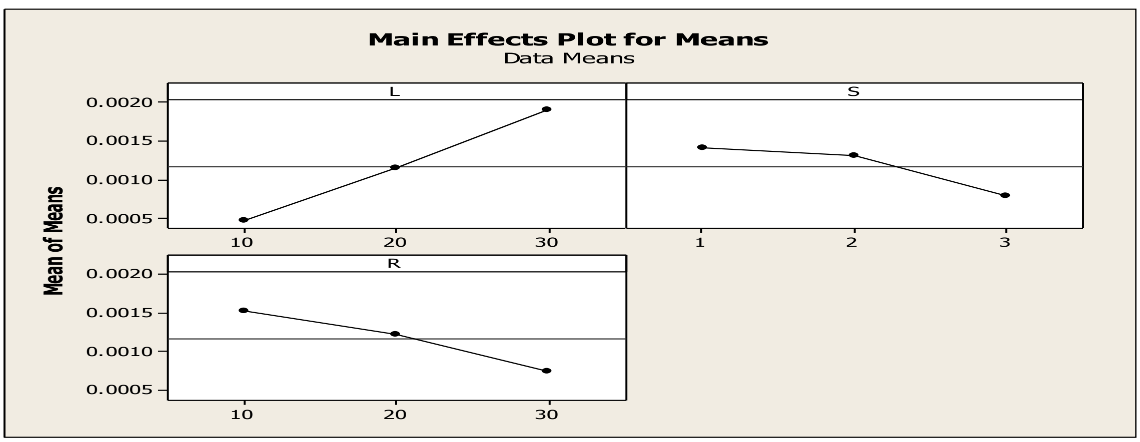


Figure 2. Mean Effect Plot

Table 5. Response Table for S/N Ratio

Level	Load, L	Sliding velocity, S	%Reinforcement, R
1	67.23	59.4	57.69
2	59.59	59.42	60.16
3	55.89	63.9	64.87
Delta	11.34	4.51	7.18
Rank	1	3	2

As the speed increases, the contact time between the disc and the specimen decreases and thus the wear rate decreases and is in agreement with Ceschini et al, (1998).The decreasing trend is also due to increase in oxidation of alloy as interfacial temp increases and this protects the pin surface from severe wear. Figure 3 indicates the optimum wear condition to obtain minimum wear rate. The optimum conditions thus arrived was low load (10 N), high sliding velocity (3 m/s) and high weight percentage of reinforcement (30 %).

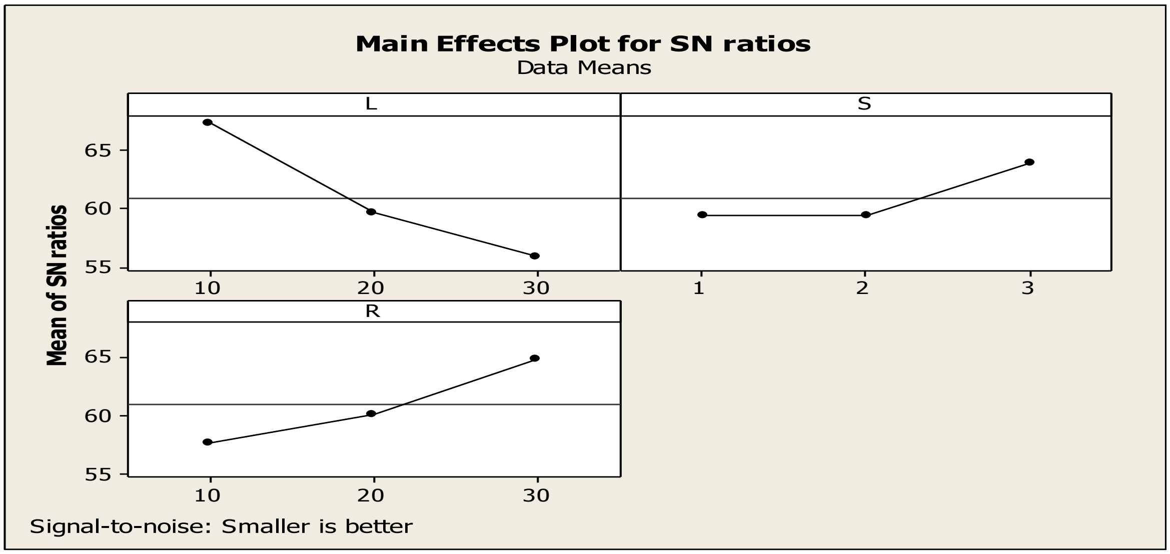


Figure 3. S/N Ratio Plot

Analysis of Variance

In optimization, ANOVA is used to check whether the conducted experimental results were valid for optimization or not. For optimization, the experimental data must be valid so that the best out of those values can be selected. So, unless the data obtained is true, optimization cannot be a success. To make sure that the obtained results are true, the variation caused in the responses is checked for chance causes and assignable causes. Only when the assignable causes outweigh chance causes, the experiment is said to be successful. ANOVA is also used to find the percentage contribution of each input parameter. This helps to determine the most contributing parameter amongst all the sources which are responsible for the variation in responses.

ANOVA partitions total variation into its appropriate components. While performing ANOVA, degrees of freedom should also be considered together with each sum of squares. In ANOVA studies with certain test error, error variance determination is very important. Obtained data are used to estimate F value of Fisher test (F-test). Variation observed (total) in an experiment attributed to each significant factor or interaction is reflected in percent contribution (P%), which shows relative power of a factor or interaction to reduce variation. Factors and interactions with substantial P% play an important role. All these calculations were done using MINITAB 16 and the results are shown in Table 6.

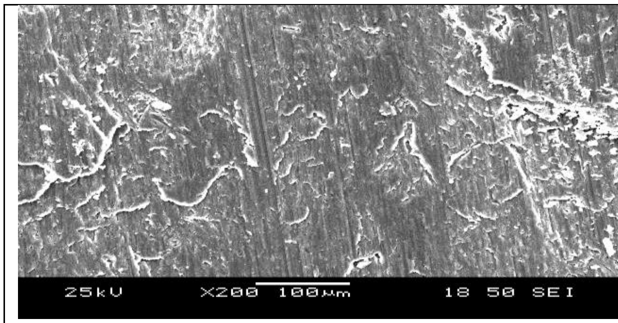
Table 6. Analysis of Variance for Wear Rate

Source	DF	SS	MS	F	P%
L	2	0.0000093	0.0000046	74.84	54.38
S	2	0.0000020	0.0000010	16.13	11.69
R	2	0.0000029	0.0000014	23.08	16.96
L*S	4	0.0000014	0.0000003	5.54	8.19
L*R	4	0.0000009	0.0000002	3.71	5.26
S*R	4	0.0000003	0.0000001	1.02	1.75
Error	8	0.0000005	0.0000001		
Total	26	0.0000171			

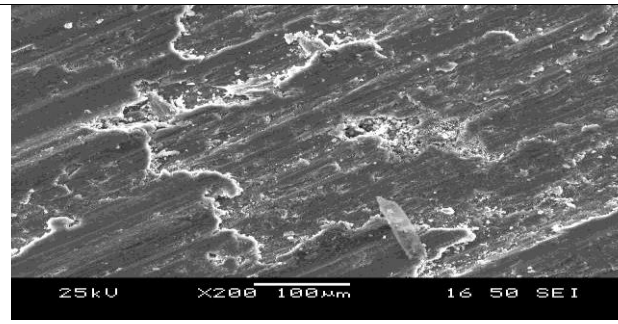
The last column of the above table (Table 6) gives the influence of each parameter on the wear rate. It gives the percentage contribution of each parameter on the total variation. From the table, it is observed that the applied load (P%=54.38) had the most significant effect on the wear rate. Hence applied load is an important control factor to be considered during wear process followed by % wt. of reinforcement (P%=16.96) and sliding velocity (P%=11.69). The interaction effect also has considerable impact on the wear rate. The interaction between load and speed is 8.19%, followed by interaction between load and reinforcement (5.26%) and interaction between speed and reinforcement (1.75%). From ANOVA and S/N ratio, it is observed that applied load has the highest contribution followed by weight percentage of reinforcements and sliding velocity.

Worn-Out Surface Analysis

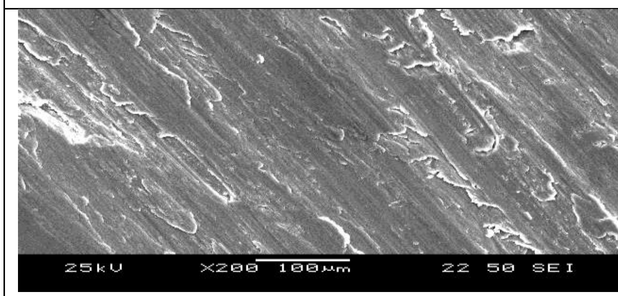
Scanning Electron Microscopy analysis was carried out for worn-out surfaces of composite samples at different processing condition. Figure 4 shows the SEM photographs of worn surfaces of composites at various load conditions. In Al-based composites with SiC and Al_2O_3 reinforcements, the reinforcements act as abrasive against the counterface, increasing counterface wear. In addition, reinforcement liberated as wear debris acts as a third-body abrasive to both the matrix and reinforcement surfaces. At 30 N load, degree of grooves formed at the worn surface are quite larger (Figure 4c) and undergo severe plastic deformation leading to severe wear compared to a 10 N load (Figure 4b). This can be seen by comparing SEM micrographs (Figure 4b & 4c). From figure 4b and 4c, it is observed as load increases more material is being removed from the pin surface and thus wear rate increases (Figure 2).The wear mechanism changes from mild wear to severe wear as load increases from 10 N to 30N. The amount of grooving in the worn surfaces of the composites is reduced with increased wt% of reinforcement indicating lower material removal and is due to higher hardness of reinforcements. The higher hardness of reinforcement will also delay the transition from mild to severe wear regime. This ensures that wear resistance increases as weight percentage of hard reinforcement increases. This is evident when comparing SEM micrograph figure 4a & 4c.Figure 4c (R-30%) reveals fine and shallow grooves in the sliding direction compared to figure 4a(R-10%). As the speed increases, the contact time between the specimen and the counterface is very less and this results in lower material removal and thus lesser grooves are seen at low speed (Figure 4d). This is evident by comparing SEM micrographs figure 4a& 4d.



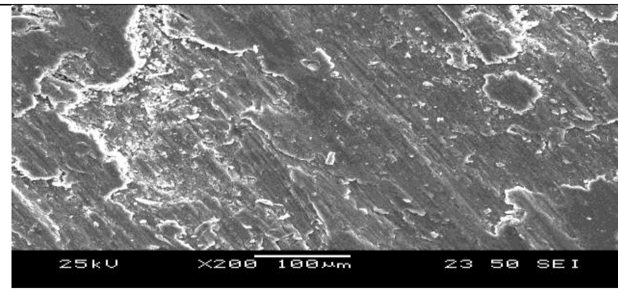
a) L – 30 N, S – 3 m/s, R– 10%



b) L – 10 N, S – 3 m/s, R – 30%



c) L – 30 N, S – 3 m/s, R – 30%



d) L – 30 N, S – 2 m/s, R – 10%

Figure 4. SEM Analysis of Worn-Out Surfaces for Different Operating Conditions

REGRESSION ANALYSIS

Regression analysis was used for prediction and forecasting. It was also used to understand which among the independent variables were related to the dependent variable, and to explore the forms of these relationships.

Regression Equation

The correlations between the main factors and the wear rate of the hybrid MMCs were obtained by multiple regressions. The obtained correlations were as follows, regression equation based with combined effect is

$$\text{Wear Rate} = -0.00159429 + 0.00019003\,L + 0.000538271\,S + 3.11839e\text{-}005\,R - 3.31511e\text{-}005\,L*S - 2.60144e\text{-}006\,L*R - 9.34165e\text{-}006\,S*R$$

The coefficient can be taken as a measure of the effect of the individual factors on the test results. It is revealed that Load factor L, has the value lesser than that of Sliding velocity factor S. It does not agree with Taguchi since the Taguchi uses a special design of orthogonal arrays and linear graphs (Sahin, 2005). The weight percentage of reinforcement factor R, has the least value of the three parameters which is in line with the Taguchi method.

Confirmation Test

Confirmation test was used to validate the regression equation and to calculate the percentage error. The regression equation is valid only for interpolation model and extrapolation cannot be done. A set of three tests were conducted to validate the regression equations with the different values of applied load and sliding velocity. Weight percentage reinforcement cannot be varied. For regression equation, sliding distance was kept constant as 1500m. Experimental wear rate and theoretical wear rate were calculated and % error between them was calculated and is shown in Table 7.

Table 7. Theoretical and Experimental Wear Rate and % Error

Load (N)	Sliding Velocity (m/s)	% Reinforcement	Experimental Wear Rate(mm^3/m)	Theoretical Wear Rate(mm^3/m)	% Error
15	1.5	10	0.00098	0.001099	12.11485
17	1.8	10	0.000933	0.000994	6.541612
25	2.5	10	0.001889	0.001858	1.636634

The error between Experimental and theoretical wear rate was less than 15%. Hence the regression equation obtained is valid.

CONCLUSION

Aluminium hybrid metal matrix composite had been successfully fabricated by stir casting method with uniform distribution of Al_2O_3 and SiC. Experiments were conducted based on Taguchi's method and was observed that load (54.38%) has the highest contribution on wear rate followed by weight percentage of reinforcement (16.96%) and sliding velocity (11.69%). S/N plot revealed the optimum processing condition (L=10 N, S= 3 m/s and R=30%) for obtaining minimum wear rate. Regression equation was generated for the present model to predict the wear rate. Confirmation experiment was carried out to validate the regression equation and comparison was made between the experimental wear rate and theoretical wear rate and the error associated was minimum (12%). Thus, Taguchi's method was used effectively to predict the tribological properties of aluminium hybrid composites.

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