Application of Taguchi to Optimize Tribological Behaviour of Aluminium A356/Mica/TiO_2 Metal Matrix Composite

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Abstract - *Aluminium A356 alloy are mainly used in automobile and aerospace applications. The present investigation deals with the study of wear behavior of Al A356/MICA/TiO_2 MMC. The specimens were fabricated by stir casting method and experiments were conducted based on the Taguchi techniques. Al A356 MMCs was reinforced with mica as primary reinforcement varied from 1.5wt%, 2.5wt%, 3.5w%t and 3wt% of secondary reinforcement as TiO_2 were prepared by stir casting method. Wear test was performed by using pin on disk apparatus and a plan of experiment based on L27 Taguchi orthogonal array is used to acquire the wear data. An analysis of variance (ANOVA) is employed to investigate the effect of controlling parameters like load, mica content and sliding speed on dry sliding wear of the composites. Smaller the better characteristic was chosen as objective to analyses the dry sliding wear behavior. Results show that sliding speed and normal affect significantly to wear.*

Keywords: Metal Matrix Composites, Stir Casting, Taguchi Techniques, Orthogonal Array, ANOVA and Wear behavior.

1. Introduction

Conventional monolithic materials have certain disadvantages or limitations in achieving optimum level of strength, toughness, wear resistance impact strength. In order to overcome these, aluminum and its alloys are reinforced with discontinuous particles which will enhance the properties of the materials. Aluminium is reinforced with particles like Al_2O_3, Sic, TiO_2 etc., which increases the mechanical and tribological properties by dispersion strengthened mechanism. Aluminium fabricated as products in many engineering fields: however, its use has limiting factors because of its poor corrosion and wear resistance. Al A356 and its alloys have been successfully developed through liquid processing route like stir casting. By using stir casting method Al356 was reinforced with TiO_2 and mica particles successfully with addition of magnesium (mg) which improve the wettability of the particles.

The Taguchi technique developed by Genechi Taguchi for optimizing process and product parameters is a tool which reduces the experiment time and coat for manufacturing. Taguchi uses lower the better, larger the better and nominal the better categories to improve quality by analyzing signal/noise ratio. The design of experiment was used to analyses the dry sliding wear problem in composite materials. In this present study Taguchi technique was used to identify the effect of load, weight% of reinforcement, sliding speed on the volumetric wear rate of Al A356 alloy reinforced with TiO_2 and Mica on pin on disc apparatus. Thus identifies the most effective control process parameter from selected reference variable by using the Taguchi method.

2. Preparation of composite

In this process, the specimens were prepared using stir casting technique. Aluminium A356 alloy was taken as the matrix material. Titanium and Mica were chosen as the reinforcement to form the hybrid composite material. Initially A356 alloy was heated to 700ºC so as to obtain the molten material in an electric furnace. The prepared mica and TiO_2 particles having mesh size in the range 100-250μ was preheated to a temperature of 450ºC for at least 1hr to remove the moisture content and absorbed gases in the particles. Degassing of molten metal was evacuated by adding hexachloro- ethane tablets. Liquid metal temperature was maintained at 700°C with sufficient viscosity. The liquid metal was stirred at a speed of 500 rpm for 10 – 15 minutes with the help of impeller to create sufficient vortex. The stir speed chosen is high enough to get a sufficient vortex for proper mixing of the reinforcement particles with the liquid metal. At the same time, stir speed is low enough to avoid the gas and air entrapment in the molten metal. The 1.5% weight preheated mica with 3% TiO_2particles was incorporated laterally in to the vortex of the molten metal. 1% magnesium was added to the molten metal to increase the wettability of the particles with the molten material. Stirring speed was maintained at 500 rpm for next 15 minutes to ensure the proper mixing. After this stage, the molten mixture was drained in to the mould. To accomplish the uniform solidification of the molten metal, the mould was preheated to 250°C for 30 minutes. Thus, particles are incorporated successfully to form hybrid composite material by using the stir casting technique. Later 2.5%wt and 3.5%wt by equal weight proportions of mica were replaced to prepare the test specimen.

3. Wear Testing Procedure

Wear test sample were fabricated as per ASTM G99 standards. The samples were cylindrical with diameter 8mm and length 30mm with flat surface at the ends. The test were conducted under fixed 3wt% TiO_2particles with normal load varying from 20N,30N,40N at different mica reinforcement percentage of 1.5%, 2.5%, 3.5% and different sliding velocity of 5,10,15m/s respectively on pin on disc machine(model) in dry condition. After each trial the pin was removed and the disc was thoroughly cleaned with acetone to remove debris. The below equation gives the relationship between volumetric wear rate dimity abrading time (t) and man lost (Δm)

$$Wv = \frac{\Delta m}{St} \text{ mm}^3/\text{s}$$

Design of Experiments (DOE) enables to model and analyse the influence of process parameters on the response variables. The parameters selected for experiments are applied load (L), reinforcement content, sliding velocity which is based on Taguchi Technique. The experiments are carried out as per L27 orthogonal array.

4. Plan of Experiments

In the present work, L27 Orthogonal array which has 27 rows and 13 columns is chosen. The selection of orthogonal array depends on the number of factor and their interaction in n umber of levels for the factors in desired experiment resolution. A total of 27 experiments were conducted based on the run order generated by the Taguchi technique. The response for the model is wear rate and coefficient of friction. In orthogonal array, 1st column is assigned to applied load, second column is assigned reinforcement content and third column is assigned to sliding velocity. The remaining columns are assigned to their interactions. The objective of the model is to minimize wear rate and coefficient of friction. The responses were tabulated and results were subjected to ANOVA. The signal to noise(S/N) ratio, which considers the multiple data points within a trial, depends on the type of characteristic being evaluated. The single to noise ratio characteristics divided in 3 categories Viz, nominal is the best, larger the better send smaller the better. In the present study smaller the better characteristics is season to analyse the dry sliding wear resistance. The signal to noise ratio for wear rate and coefficient of friction using smaller the better characteristics given by Taguchi is as follows Y^2

$$\frac{S}{N} = -10 \log (1/n\ \Sigma Y^2_i)$$

Where "n" is the number of observations Y_i is the measured value of wear rate. The signal to noise ratio shows the average of selected characteristics for each level of the factor. This table include the Frank based on the Delta statistics which compares the relative value of the effect. Signal to noise ratio is a response which consolidates repetition and the effect of noise level in to the point. Analysis of variance of the S/N ratio is performed to identify the statistically significant parameters.

5. Results and Discussion

The Effects of the tribological test parameters such as load, sliding speed and distance on wear rate and coefficient of friction have been optimized and evaluated using Taguchi technique, with appropriate signal to noise ratio and analysis of variance (ANOVA). These design parameters are unique and inherent future of the process that influence and decide the composite performance. The parameters that highly influence the wear rate and coefficient of friction have been determined by the rank value which has been obtained from the difference between the maximum and minimum value (delta) of the mean of signal to noise ratio.

5.1 Result Statistical Analysis of Experiments

By conducting the experiment as per the orthogonal array the results for various combinations of parameter were obtained. The measured results were analyzed using commercial software Minitab 16 specifically used in DOE applications. Table 4 shows the experimental results average of two repetitions for wear rate and coefficient of friction. The experimental values are transformed into a signal to noise ratio to measure the quality characteristics. The effect of control parameters as load, reinforcement % and sliding speed on wear rate and COF has been analyzed using signal to noise ratio response table. The ranking of process parameters using signal to noise ratio that has been obtained for various Parameter levels for wear rate and COF are given in the response table and respectively for the composite. The control factor are statistical significance in the signal to noise ratio and it could be observed that the reinforcement % is a dominant parameter on the wear rate and coefficient of friction followed by applied load and sliding speed. Figures 1,2,3,4 show the influence of process parameters on wear rate and coefficient of friction graphically. The analysis of these experimental results using signal to noise gives the optimum conditions resulting in minimum wear rate and coefficient of friction. The optimum conditions for wear rate and coefficient of friction are shown in table 2 and 3.

Table :1 Orthogonal Array

Exp No.	Applied Load in (N)	Wt % of Reinforcement	Sliding speed (m/s)	Wear Rate (mm^3/min)	S/N ratio in (db)	COF	S/N ratio in (db)
1	20	1.5	5	0.003650	48.7541	0.376	8.4962
2	20	1.5	10	0.003440	49.2688	0.331	9.6034
3	20	1.5	15	0.002045	53.7861	0.312	10.1169
4	20	2.5	5	0.003019	50.4027	0.341	9.3449
5	20	2.5	10	0.002245	52.9757	0.336	9.4732
6	20	2.5	15	0.001945	54.2216	0.310	10.1728
7	20	3.5	5	0.002868	50.8484	0.356	8.9710
8	20	3.5	10	0.019390	34.2484	0.324	9.7891
9	20	3.5	15	0.001800	54.8945	0.306	10.2856
10	30	1.5	5	0.004074	47.7996	0.387	8.2458
11	30	1.5	10	0.003141	50.0586	0.356	8.9710
12	30	1.5	15	0.002492	52.0690	0.322	9.8429
13	30	2.5	5	0.003092	50.1952	0.372	8.5891
14	30	2.5	10	0.002468	52.1531	0.347	9.1934
15	30	2.5	15	0.002100	53.5556	0.321	9.8699
16	30	3.5	5	0.002905	50.7371	0.343	9.2941
17	30	3.5	10	0.002356	52.5565	0.334	9.5251
18	30	3.5	15	0.002188	53.1991	0.318	9.9515
19	40	1.5	5	0.005000	46.0206	0.419	7.5557
20	40	1.5	10	0.003962	48.0417	0.370	8.6360
21	40	1.5	15	0.002905	50.7371	0.361	8.8499
22	40	2.5	5	0.004439	47.0543	0.401	7.9371
23	40	2.5	10	0.003440	49.2688	0.364	8.7780
24	40	2.5	15	0.002661	51.4991	0.354	9.0199
25	40	3.5	5	0.004514	46.9088	0.389	8.2010
26	40	3.5	10	0.003291	49.6534	0.352	9.0691
27	40	3.5	15	0.002692	51.3985	0.344	9.2688

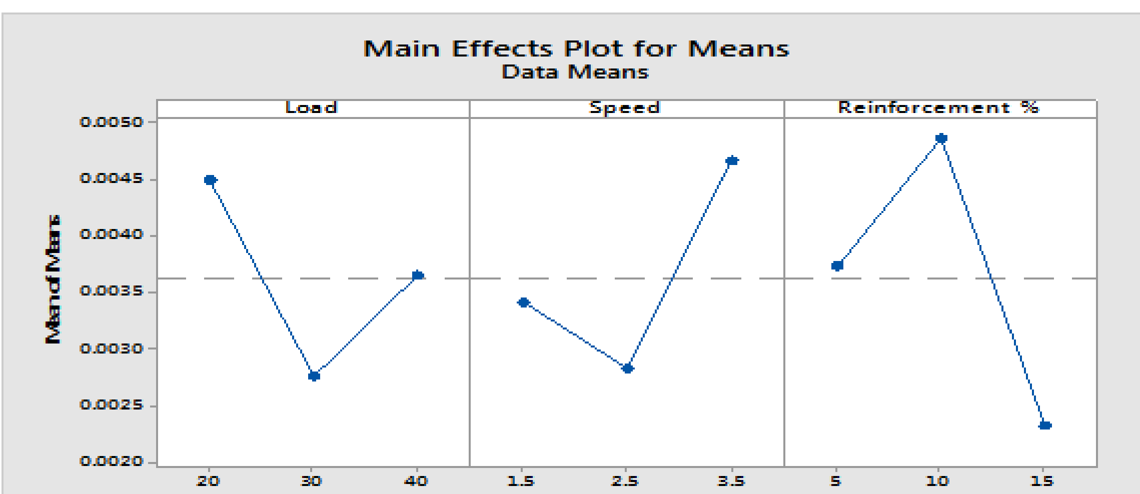

Fig.1 Main effect plot for means- Wear Rate

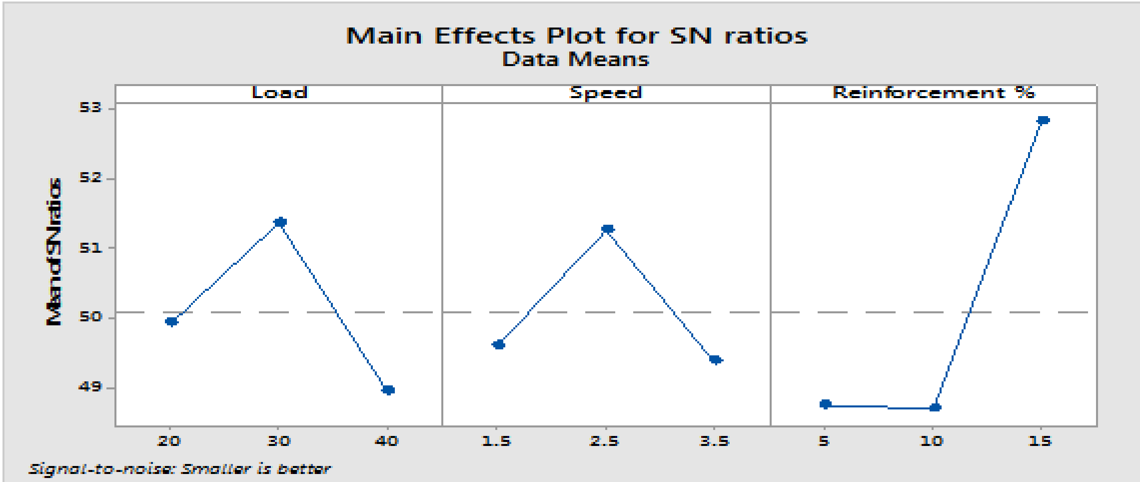

Fig.2 Main effect plot for S/N- Wear Rate

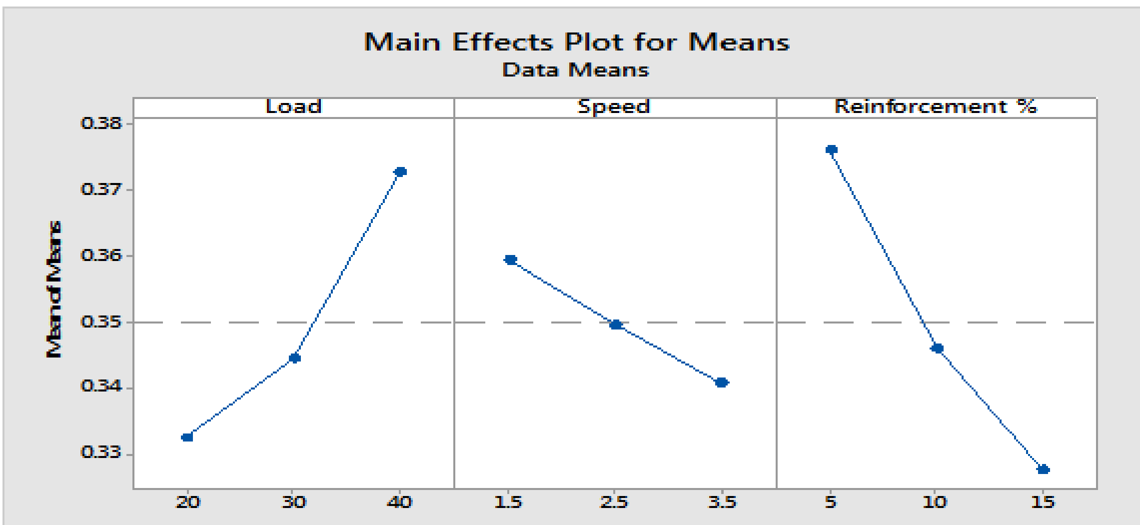

Fig.3 Main effect plot for means- Co-efficient of Friction

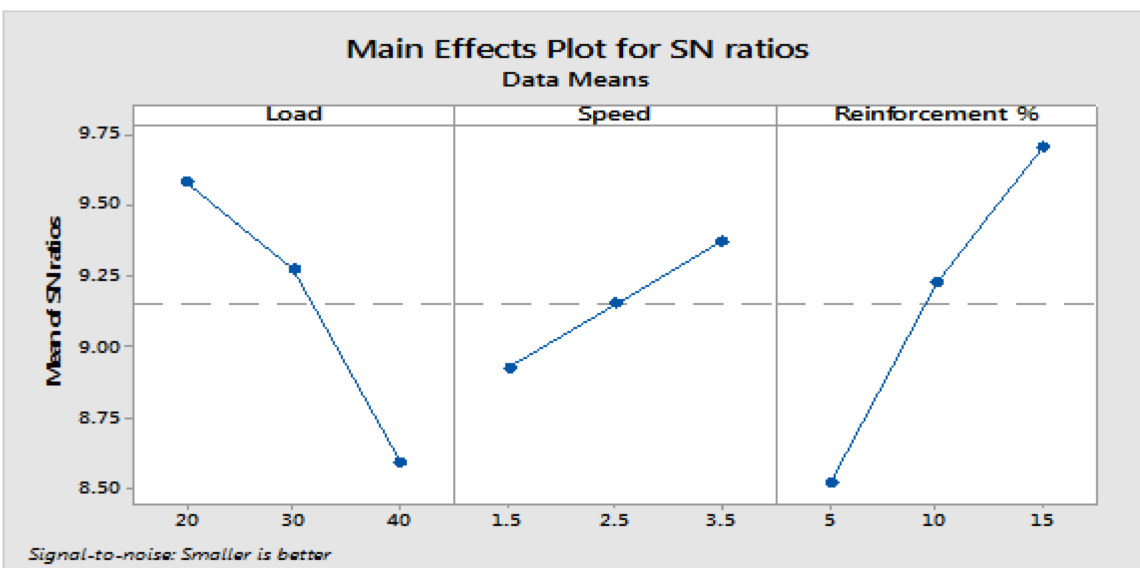

Fig.4 Main effect plot for S/N- Co-efficient of Friction

Table: 2 Response Table for signal to Noise ratios- Smaller is better (Wear Rate)

Level	Load	Speed	Reinforcement %
1	49.93	49.62	48.75
2	51.37	51.26	48.69
3	48.95	49.38	52.82
Delta	2.42	1.88	4.13
Rank	2	3	1

Table:3 Response Table for signal to Noise ratios- Smaller is better (Co-efficient of Friction)

Level	Load	Speed	Reinforcement %
1	9.584	8.924	8.515
2	9.276	9.153	9.226
3	8.591	9.373	9.709
Delta	0.993	0.449	1.194
Rank	2	3	1

5.2 Analysis of Variance Result for Wear Test

The experiment results were analyzed the ANOVA which is used to investigate the influence of considered wear parameters like applied load sliding speed and sliding distance that significantly affect the performance measure. By performing ANOVA it can be decided which independent factor dominates over the other and the percentage contribution of that particular independent variable. Table and show the ANOVA results for wear rate and coefficient of friction for three factors varied at three levels and interactions of those factors. This analysis is carried out for a significant level of α=0.05 for a confidence level of 95%. Sources with a P- value less than 0.05 were considered to have a statistical is significant contribution to the performance measures. In table and the last column shows the percentage contribution (Pr) for each parameters on the total variation indicating their degree of influence on the result.

Table :4 ANOVA for Wear Rate (mm^3/m)

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Pr(%)
Load	2	0.0000058	0.0000058	0.0000029	99.56	0.000	31.5
Speed	2	0.0000026	0.0000026	0.0000013	45.02	0.000	14.1
Reinforcement %	2	0.0000086	0.0000086	0.0000043	147.55	0.000	46.8
Load*Speed	4	0.0000001	0.0000001	0.000000	0.72	0.604	0.5
Load*Reinforcement %	4	0.0000004	0.0000004	0.0000001	3.66	0.056	2.2
Speed*Reinforcement %	4	0.0000005	0.0000005	0.0000001	4.54	0.033	2.7
Error	8	0.0000004	0.0000004	0.0000000			2.2
Total	26	0.0000184					100

Table:5 ANOVA for Coefficient of Friction

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Pr(%)
Load	2	0.0076750	0.0076750	0.0038375	73.24	0.000	35.7
Speed	2	0.0015692	0.0015692	0.0007846	14.97	0.002	7.3
Reinforcement %	2	0.0107612	0.0107612	0.0053806	102.69	0.000	50
Load*Speed	4	0.0002093	0.0002093	0.0000523	1.00	0.462	1.0
Load*Reinforcement %	4	0.0003453	0.0003453	0.0000863	1.65	0.254	1.6
Speed*Reinforcement %	4	0.0005344	0.0005344	0.0001336	2.55	0.121	2.5
Error	8	0.0004192	0.0004192	0.0000524			1.9
Total	26	0.0215134					100

It can be observed from the table that the reinforcement % has the highest influence (P=46.8%) followed by load (31.5%) and speed (14.1%) on the wear rate. Among the interaction terms, interaction between speed and reinforcement % is 2.7% on the wear rate. Other interactions are above the confidence level of 0.05, therefore those interactions can be neglected. The table shows the ANOVA for coefficient of friction, from which it can be observed that reinforcement % has the highest influence (P=50%) followed by load (P=35.7%). From the ANOVA it is inferred that the reinforcement % has the highest contribution on wear rate and coefficient of friction followed by load and speed.

5.3 Multiple Linear Regression Models

A multiple linear regression model is developed using statistical software MINITAB 17. This model gives the relationship between an independent variable and a response variable by fitting a linear equation to observed data. Regression equation generated establishes correlation between the significant terms obtained from ANOVA analysis, namely load, reinforcement content, sliding speed and their interactions.
The regression equation developed for wear rate is

Wr=0.00447+0.000054Load-0.000690Reinforcement %-0.000002Sliding speed Eqn.1

The regression equation developed for Coefficient of friction is

COF=0.361+0.00201 Load -0.00933 Reinforcement %--0.000035 Sliding speed Eqn.2

From equation 1 and 2 it is observed that reinforcement % plays important role on wear rate and Coefficient of friction followed by load and sliding speed. From equation 1 and 2 it can be inferred that, the negative value of reinforcement % reveals that increase in reinforcement % decreases the wear rate and coefficient of friction. This can be attributed to oxidation of aluminium alloy, which forms the oxide layer at higher interfacial temperature thereby decreasing the wear rate. Figure 5,6,7 show the Scanning Electron micrographs of various specimens.

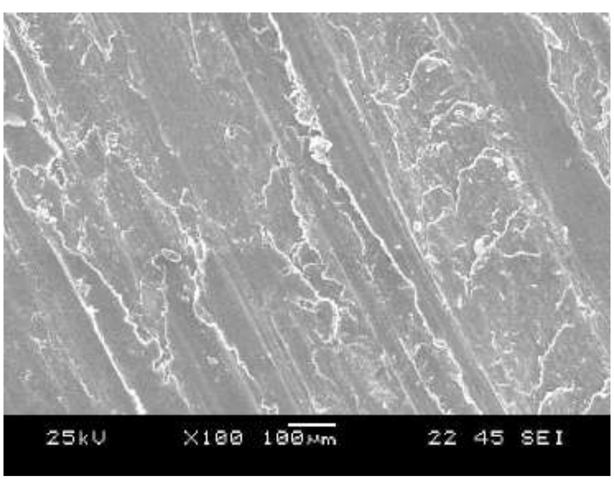

Fig.5 Load=40N, Reinforcement%=3.5wt %
Speed= 15m/s

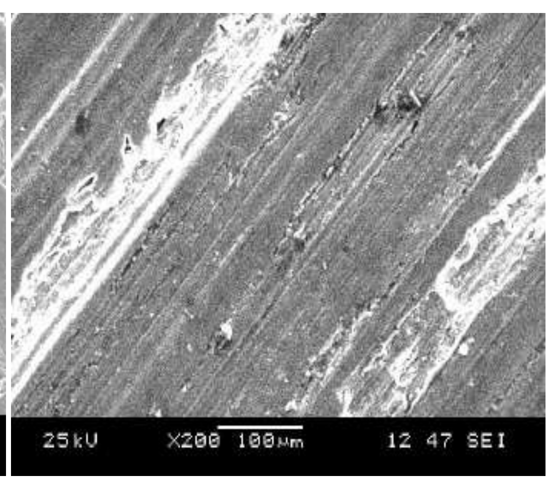

Fig.6 Load=40N, Reinforcement%=3.5wt %
Speed= 10m/s

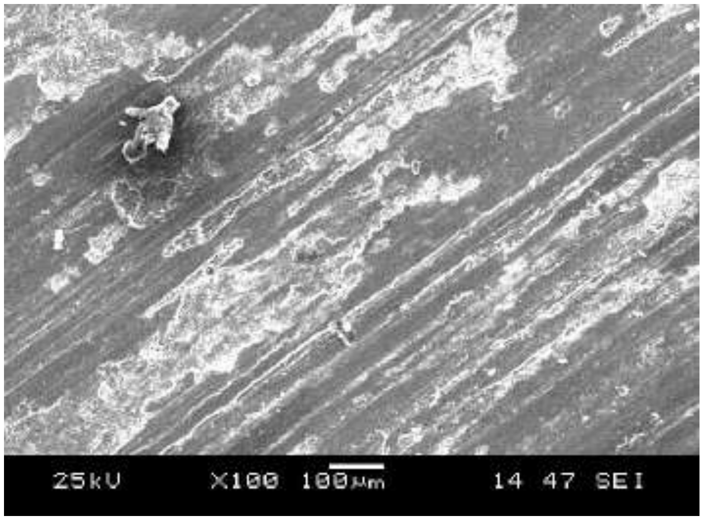

Fig.7 Load=40N, Reinforcement%=3.5wt %
Speed= 5m/s

6. Conclusions

Following are the conclusions made from the dry wear test using Taguchi technique.

a) Reinforcement % has the highest influence (P=46.8%) followed by load (31.5%) and speed (14.1%) on the wear rate.
b) Reinforcement % has the highest influence (P=50%) followed by load (P=35.7%)and speed (7.3%) for coefficient of friction.
c) Incorporation of mica as a primary reinforcement increases the wear resistance by forming a protective layer between pin and counter face.
d) Inclusion of TiO2 as a secondary reinforcement also has significant effect on the wear behavior.
e) Regression equation generated for the present study was used to predict the wear rate and coefficient of friction of composites for intermediate conditions with reasonable accuracy.

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