Fabrication of LM25/SiO$_2$ Metal Matrix Composite and Optimization of Wear Process Parameters Using Design of Experiment

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A B S T R A C T

LM25 aluminium alloy reinforced with 15 wt% SiO$_2$ metal matrix composite was fabricated by liquid metallurgy technique. Microstructure of the fabricated composite specimen was observed using inverted metallurgical microscope and result showed uniform distribution of reinforcement particles in the matrix. The dry sliding wear behaviour of LM25/SiO$_2$ composite was analyzed by conducting experiments using pin-on-disc tribometer. Taguchi's method was used for designing the number of experiments and L$_{16}$ orthogonal array was developed for wear analysis. Optimization of parameters like applied load (10 N, 20 N, 30 N, 40 N), sliding velocity (0.5 m/s, 1 m/s, 1.5 m/s, 2 m/s) and sliding distance (500 m, 1000 m, 1500 m, 2000 m) was done using Signal-to-Noise ratio analysis and Analysis of Variance. 'smaller-the-better' characteristic was chosen to analyze the dry sliding wear behaviour. Results found that load (69.17 %) had the highest impact on wear rate followed by sliding velocity (18.04 %) and sliding distance (1.5 %). The regression equation was developed and it was validated with confirmatory experiment. Scanning Electron Microscope analysis was done to observe the mechanism of the worn out composite specimen and found more delamination at the load of 40 N.

1. INTRODUCTION

In the last two decades there is a continuous development in the material technology and the main contribution is to reduce the cost and to meet the global demands of engineering requirement. Engineering materials have limitations to meet the requirement of mechanical and tribological properties. To overcome these problems, Metal Matrix Composites (MMCs) are used due to their excellent strength, stiffness, high specific modulus, high specific strength, good tribological properties, low coefficient of thermal expansion, thermal conductivity and damping capacity [1-2]. MMCs are used in

number of applications such as automobile, aerospace, and marine industries [3]. Aluminum is used as matrix metal due to their nature of physical and mechanical properties which are closely suitable for MMCs. A comparison of mechanical properties of unreinforced Al 6061 alloy and Al 6061/12 wt% Titanium Diboride (TiB_2) MMCs manufactured through in-situ process was made. Result revealed that mechanical properties of MMCs were higher than unreinforced alloy [4].The tensile strength of Al/5 Vol. % of Silicon Carbide (SiC) composite fabricated by stir casting route was found high than the same composite fabricated by powder metallurgy technique [5].

Dry sliding wear behavior of Al 6061 composite reinforced with varying wt% (2, 6, 10 and 15) of Beryl was investigated and found that specific wear rate was decreased linearly with increasing wt% of Beryl [6]. Investigation on adhesive wear behavior of Al 2219/titanium carbide (TiC) MMCs revealed that addition of TiC particles improved the wear resistance of the composite [7]. Dry sliding wear behavior of LM 6 aluminum alloy reinforced with 5 wt% of Graphite and 10 wt% of Titanium Oxide (TiO_2) hybrid composite was studied and found that presence of graphite particle decreased the wear rate and presence of TiO_2 particle increased the mechanical properties of the composite [8]. Effect of varying alumina (Al_2O_3) particle wt% (3, 6, 9 and 12) and its particle size (149, 105, 74 μm) on wear behavior of Al 7075 composite have been studied and observed that wear rate decreased with decrease in particle size and with increase in weight percentage of the reinforcement [9]. Effect of Zirconium Silicate ($ZrSiO_4$) particle size (53-105 μm) on dry sliding wear behavior of Al-12wt%Si-5wt%Sn composite fabricated by spray forming technique was analyzed and lesser wear rate was observed with the particle size of 53 μm [10]. Effect of wear parameters on Al 2219 alloy reinforced with 3wt% of Boron Carbide (B_4C) and 3, 4 and 5wt% of Molybdenum Disulphide (MoS_2) hybrid MMCs were investigated and found that wear rate increased initially with sliding distance and sliding velocity and thereafter decreased [11].

The process parameters are well optimized by Taguchi Design of Experiment (DOE) [12,13]. There are three main phases in DOE process

such as planning phase, conducting phase and analysis interpretation phase. Among these three phases, the most important phase is planning phase, so one has to give more emphasis to that phase. Dry sliding wear resistance of Al 7075 alloy reinforced with different reinforcement particles such as Al_2O_3, SiC and cenosphere have been investigated through Taguchi's method and found that applied normal load was the most influential parameter for Al_2O_3 and cenosphere reinforced composite, and for SiC reinforced composite, sliding velocity was the most influential factor. It is also observed that SiC reinforced composite showed least wear rate compared to Al_2O_3 and cenosphere reinforced composites [14]. Effect of dry sliding wear parameters of Al 6351 alloy reinforced with fly ash (10 μm) particles were also analyzed using Taguchi technique and found applied load had greatest impact on wear rate followed by sliding velocity and weight percentage of reinforcement [15].The wear rate of Al6061T6 alloy reinforced with 10% SiC/10% Al_2O_3/5% Graphite hybrid MMCs were analyzed through regression model analysis and observed that wear rate increased with applied load and decreased with sliding velocity and sliding distance [16].

Based on the above literature survey it is observed that Al-SiO_2 (Silicon Dioxide) MMCs has not been fully explored. Hence the aim of the present work is to fabricate LM25Al/15 wt % of SiO_2 MMCs and investigate its dry sliding wear characteristics through DOE technique.

2. MATERIAL SELECTION

LM25 aluminium alloy was chosen as the matrix material due to its properties such as excellent castability, good machinability and light weight [17]. This alloy is used to cast intricate shape of the automobile and aerospace components [18]. The elemental composition of this alloy is shown in the Table1.

Table 1. Elemental Composition of LM25 Al alloy.

Compos.	Si	Fe	Cu	Mn	Zn	Mg	Ti	Al
Range	6.5-7.5	0-0.55	0-0.2	0-0.35	0-0.1	0.2-0.4	0-0.2	Bal.
wt%	7.34	0.4	0.1	0.09	0.1	0.38	0.1	Bal.

SiO_2 (30-45 μm) with 15 wt% was chosen as reinforcement particles due to its higher wear

resistance properties and is used as refractory in thermal protection system. The densities of aluminum alloy and SiO_2 particles were 2.68 g/cm^3 and 2.62 g/cm^3 respectively. The $LM25/SiO_2$ composite is well suited for automobile application especially for the manufacture of engine piston [19].

3. FABRICATION OF COMPOSITE

The $LM25Al/15wt\%SiO_2$ composite was fabricated by stir casting route as this is the most economical and result oriented process for fabrication of MMCs which has been adopted by many researchers [20]. The aluminium ingots were taken in the graphite crucible and kept inside the electric resistance furnace (Fig. 1), where melting occurs between the temperature range of 600-700 °C under inert argon gas atmosphere in order to prevent the reaction between molten metal and ambient air to avoid the occurrence of casting defects like porosity, blow holes, etc.
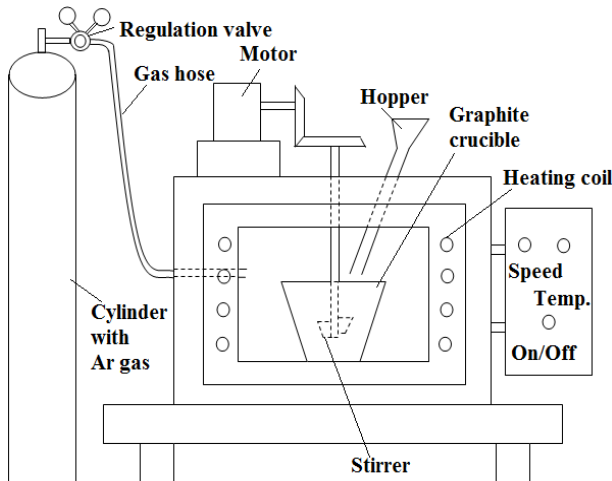

Fig. 1. Schematic view of Melting furnace.

The preheated (300 °C) reinforcement particles (SiO_2) were gradually added to the melt and stirring was carried out at a speed of 300 rpm for 5 minutes to get homogeneous distribution of SiO_2 particles in the matrix. The molten mixture was then poured at 710 °C into the mild steel mould (180 mm in length and 40 mm in diameter) and allowed to solidify.

4. MICROSTRUCTURAL ANALYSIS

The microstructure of $LM25/SiO_2$ composite was observed by Zeiss Axiovert 25 CA Inverted Metallurgical Microscope. For microstructural analysis, the composite specimen was cut into small piece and was mechanically polished initially using SiC emery paper size of 400, 600 and 1000 grade. Further, polishing was done on the specimen using velvet cloth with alumina powder in order to obtain smooth surface finish. Then these specimens were properly etched with keller's reagent to observe the microstructure of the composite.

5. WEAR TEST

Dry sliding wear experiment was conducted on the $LM25Al/15wt\%SiO_2$ composite using pin-on-disc tribometer. The test specimens of 10 mm in diameter and 35 mm in length were machined from fabricated composite. The stationary holder was used to hold the composite specimen (pin) at one end and the loads were provided by fixed arm with pulley arrangements connected at other end. A Group of weights connecting the fulcrum through the beam provides normal force on the pin. The rotating speed of the disc was controlled so that constant contact was provided at various test parameters. The rotating disc and pin were properly cleaned by SiC emery paper with the grade 1/0 and 2/0 in order to ensure the fresh contact between pin and counterface. The weighing balance having an accuracy of 0.0001 g was used to weigh the specimen prior to and after each experiment.

6. PLAN OF EXPERIMENT

L_{16} orthogonal array was selected for the present investigation and the degree of freedom for the orthogonal array should be greater than or equal to, the sum of the variables [21]. The parameters and the corresponding levels are shown in Table 2. The experiment was conducted to analyze the effect of dry sliding wear parameters on Al MMCs and the wear rate results were subjected to Analysis of Variance (ANOVA) and S/N ratio analysis.

Table 2. Process parameters and their levels

Level	Load (N)	Sliding Velocity (m/s)	Sliding Distance (m)
1	10	0.5	500
2	20	1	1000
3	30	1.5	1500
4	40	2	2000

7. RESULTS AND DISCUSSION

Microstructural results, Signal-to-Noise (S/N) ratio, dry sliding wear behaviour, Analysis of Variance (ANOVA) are discussed in the following subsections.

7.1 Microstructural Results

The microstructure of $LM25/SiO_2$ reinforced composite and SEM image of SiO_2 reinforcement particles are shown in Figs. 2 and 3 respectively.
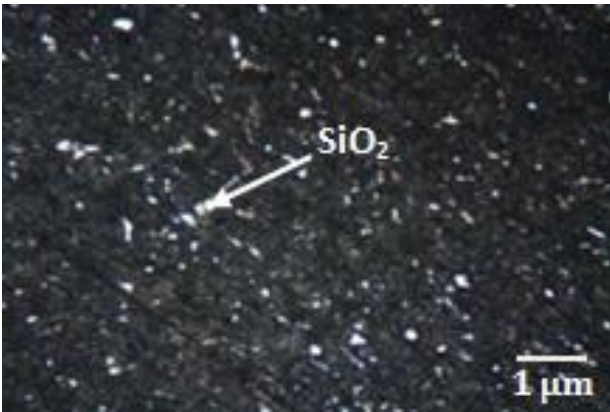

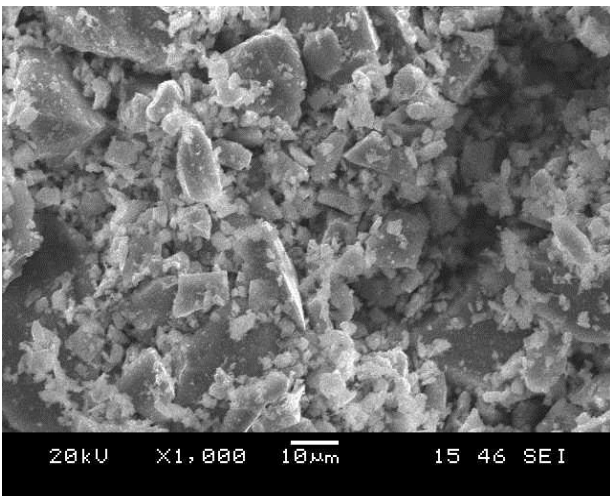**Fig. 2.** Microstructure of $LM25/SiO_2$ composite.

Fig. 3. SEM image of SiO_2 particles.

From Fig. 2, it is seen that the reinforcement particles were uniformly distributed over the matrix. This homogeneous distribution was due to casting parameters such as constant stirring speed (300 rpm) and stirring time (5 min).

7.2 Dry sliding wear behavior

Based on L_{16} orthogonal array, dry sliding wear rate of the $LM25/SiO_2$ composite was calculated and their results are listed in Table 3.

Table 3. Dry sliding wear experimental results

S. No	Load (N)	Sliding Velocity (m/s)	Sliding Distance (m)	Wear Rate (mm^3/m)
1	10	0.5	500	0.00218
2	10	1	1000	0.00225
3	10	1.5	1500	0.00099
4	10	2	2000	0.00092
5	20	1	500	0.00176
6	20	0.5	1000	0.00169
7	20	2	1500	0.00178
8	20	1.5	2000	0.00186
9	30	1.5	500	0.00233
10	30	2	1000	0.00247
11	30	0.5	1500	0.00275
12	30	1	2000	0.00291
13	40	2	500	0.00273
14	40	1.5	1000	0.00278
15	40	1	1500	0.00447
16	40	0.5	2000	0.00401

7.3 Signal-to-Noise Ratio analysis

Signal-to-Noise ratio (S/N Ratio) was used to analyze the effect of parameters such as sliding velocity, sliding distance and load on wear rate. These analyses were done using Minitab software. The S/N ratio was calculated based on 'smaller-the-better' characteristic given by Taguchi and is as follows:

$$S/N \text{ ratio} = -10 \, Log_{10} \left[\frac{1}{n} \sum y^2 \right]$$

where 'y' is response value and 'n' is number of observation.

Response table for S/N ratio is shown in Table 4 where delta value was used to figure out the most extremely affecting parameter on wear rate and highest delta value means that parameter causes more wear. The delta value gives the discrepancy between the peak S/N ratio value and the lowest S/N ratio value of the parameter. From Table 4, it is observed that wear rate was majorly affected by load parameter followed by sliding velocity and sliding distance.

Table 4. S/N Ratio Response table.

Level	Load (N)	Sliding Velocity (m/s)	Sliding Distance (m)
1	57.58	58.32	56.32
2	62.24	52.7	54.16
3	55.06	59.55	56.18
4	52.05	56.35	60.26
Delta	10.19	6.85	6.11
Rank	1	2	3

7.4 Influence of Parameters on Wear Rate

S/N ratio and mean plot for the wear rate are graphically shown in Figs. 4 and 5 respectively.
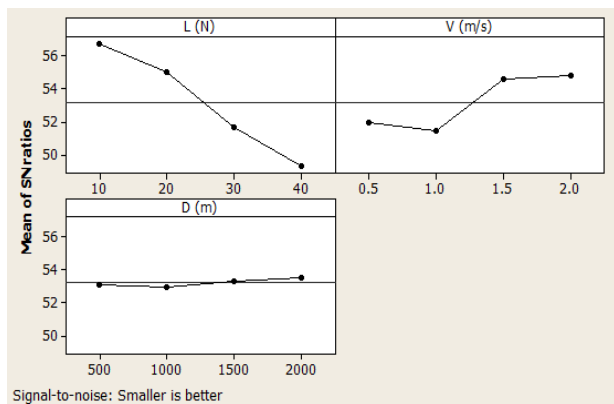
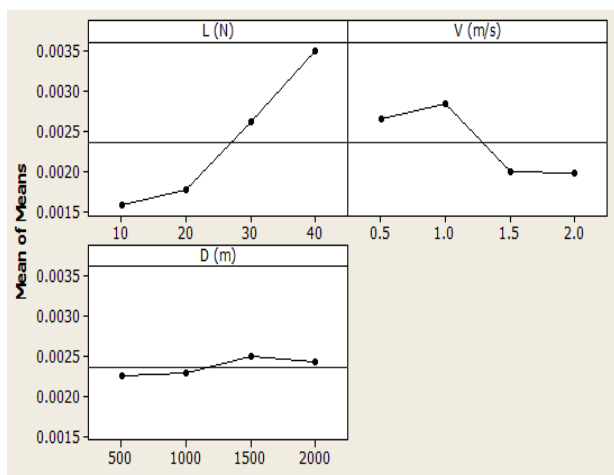

Fig. 4. Main Effects Plot for S/N ratio.

Fig. 5. Main Effects Plot for Means.

The S/N ratio plot (Fig.4) gives the optimum value (L=10 N, V=2 m/s and D=2000 m) of process parameters to improve the wear resistance of composite and mean plot describes the trend of responses for the three parameters.

7.5 Impact of load on wear behavior

From Fig. 5, for the load between 10 N to 20 N, the wear rate of the composite increased slightly due to lesser contact between the composite surface and counterface and material removal was minimum. As the load increased from 20 N to 40 N, wear rate of the composite increased as the load pushed the specimen strongly against the disc and consequence of that higher amount of stress acted on the harder and sharper reinforcement particles. This caused greater rubbing action which underwent plastic

deformation and decreased the strength between matrix and reinforcement particles. As a result of this, some of the reinforcement particles get fractured and the wear rate progressively moved to the matrix and more material was removed from the composite specimen. In addition to that, the higher strain hardening tendency in the subsurface layer of the composite also caused delamination and resulted in higher wear rate and the similar trend was observed in previous study [22].

7.6 Impact of sliding velocity on wear behaviour

From Fig. 5, it was observed that the wear rate of the composite increased and then decreased with sliding velocity. From the sliding velocity of 0.5 m/s to 1 m/s, the contact time between composite and counterface material was high which led to increase the interfacial temperature. Due to this, the reinforcement particles tend to lose their load bearing capacity which resulted in higher wear rate. In addition to decrease of reinforcement particle strength, the increase of matrix contact with counterface material was also attributed to increased wear rate of the composite. On the other hand, the removal of matrix material was reacted with atmospheric air and forms a non-porous oxide layer over the composite surface. The strong formation of an oxide layer protected the composite and consequently wear rate of the composite reduced with the increase of sliding velocity from 1 m/s to 1.5 m/s. From the sliding velocity of 1.5 m/s to 2 m/s the wear rate of the composite decreased continuously due to lesser contact time between the composite and counterface material and the similar trend was observed in previous investigation [23].

7.7 Impact of sliding distance on wear behaviour

From Fig. 5, an increase in wear rate was observed for the sliding distance between 500 m to 1500 m. Initially during sliding, the hard reinforcements protruded from the composite surface acted as sharp asperities and produced non uniform contact between the specimen and counterface which in turn increased wear rate. Further increase of sliding distance from 1500 m to 2000 m, the sharper and harder reinforcement particles get compressed

between the sliding surfaces and smoothened which allowed uniform contact with the counterface and thereby wear rate decreased, where similar behavior was also observed in previous study [24].

7.8 Analysis of Variance

Analysis of Variance (ANOVA) was used to find out the most influencing design factors which affect the performance characteristics (Table 5).

Table 5. ANOVA results for wear rate.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	P (%)
L (N)	3	9.2E-06	9.2E-06	3E-06	12.09	0.006	69.17
V (m/s)	3	2.4E-06	2.4E-06	8E-07	3.2	0.105	18.04
D (m)	3	2E-07	2E-07	1E-07	0.21	0.889	1.5
Error	6	1.5E-06	1.5E-06	3E-07			11.2
Total	15	1.3E-05					

The ANOVA was conducted for the confidence level of 95 % and significance level of 5 %. The percentage contribution of each parameter was shown in the last column of ANOVA. The P value of the load parameter from the table was found to be less than 0.05. From the results, it was concluded that load (69.17 %) had higher impact on wear rate followed by sliding velocity (18.04 %) and sliding distance (1.5 %).

8. LINEAR REGRESSION ANALYSIS

The linear regression equation was developed by using Minitab statistical software. This analysis was used to identify the correlation between predicted variable and the response variable.

The regression equation for wear rate is as follows:

$$W = 0.00127 + 0.000066\,L - 0.000581\,V + 0.0000001\,D \quad (1)$$

where L is the applied load in (N), V is sliding velocity in (m/s), D is sliding distance in (m).

The positive/negative sign of this equation (1) indicated the wear behaviour of composite. The positive sign indicated increase in wear rate and negative sign indicated decrease in wear rate with parameter. The confirmation test was performed with parameters other than selected parameters as shown in Table 6 and the wear test was conducted for the preferred levels. Then the results observed from experimental wear rate were compared with regression wear rate and found an error less than 7 %.

Table 6. Selected Parameters and Results for confirmation experiment.

S. No	Load (N)	Sliding Velocity (m/s)	Sliding Distance (m)	Experim. wear rate (mm³/m)	Regression wear rate (mm³/m)	Error %
1	15	0.8	750	0.00185	0.00179	3.2
2	25	1.2	1250	0.00211	0.00222	5.2
3	35	1.6	1750	0.00248	0.00265	6.8

The regression wear rate results were closely similar to experimental wear rate with minimum error and hence the developed model had higher efficiency to analyze the wear rate of composite.

9. SCANNING ELECTRON MICROSCOPE ANALYSIS

The Scanning Electron Microscope (SEM) analysis was conducted on the worn out composite specimen to observe the dry sliding wear mechanism. This analysis was conducted for different loading condition (Fig. 6 a-d) at a constant sliding velocity of 1.5 m/s as the wear rate of the composite was mostly impacted by applied load. At a load of 10 N (Fig. 6a), minimum material removal on the composite specimen was observed. Also, it was observed that the wear debris formation on the worn out surface was less due to less ploughing effect. From Fig. 6 b (20 N load), more grooves were observed which led to more material removal on the specimen due to increase in sliding friction between those surfaces. As the load increased to 30 N (Fig. 6c), severe scratches and further increase in delamination on worn out surface was observed and this was due to adhesion between those two surfaces. The rate of wear was accelerated on composite when load reached to 40 N (Fig. 6 d) and increased depth of grooves on the surface was observed. Thus it is concluded that load was the dominant parameter on wear rate of the composite which was confirmed with the SEM analysis. The worn out composite at optimum condition (L=10 N, V=2 m/s, D=2000 m) is shown in Fig. 7 and observed minimum delamination and grooves which reveled lesser wear rate.
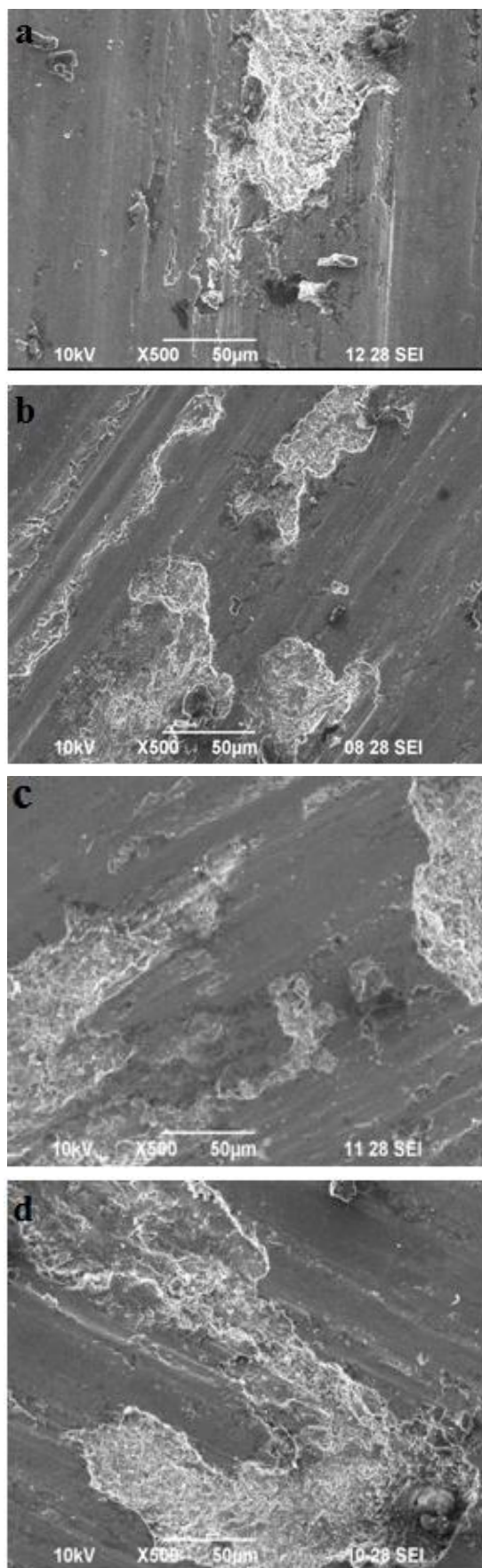
Fig. 7. SEM image at optimum condition.

10. CONCLUSION

The LM25/SiO$_2$ composite was successfully fabricated by stir casting technique. Microstructure of the composite was observed and result showed uniform distribution of reinforcement particles in the matrix. The process parameters were analysed using Taguchi technique. From the ANOVA analysis, it was found that load (69.17 %) had major impact on wear rate followed by sliding velocity (18.04 %) and sliding distance (1.5 %). The regression equation was developed and it was validated with the confirmatory results. SEM analysis revealed the occurrence of maximum wear at high load condition. The present research on the dry sliding wear of aluminium MMC can be used for applications where dry sliding wear resistance is of major consideration.

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Fig. 6. SEM images of worn out specimens at various conditions, a) L=10 N, D=1500 m, b) L=20 N,D=2000 m, c) L=30 N,D=500 m, and d) L = 40 N, D=1000 m.
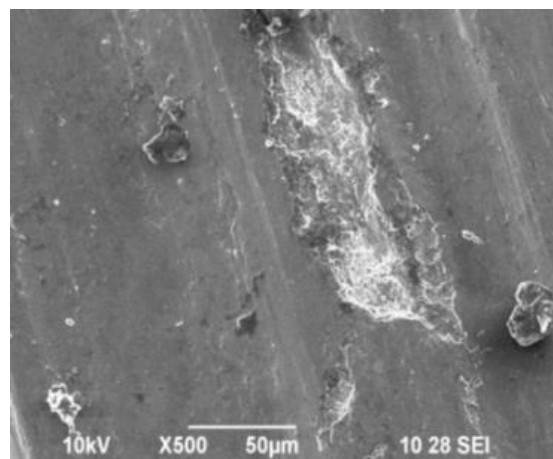
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