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Parametric Analysis on Non-Lubricated Wear Over Hybrid Aluminium Metal Matrix Composite Material by Rsm

R. KOUSIK KUMAAR#1, K. SOMASUNDARA VINOTH#2, M. KAVITHA#3,
#1Department of Production Engineering, #2Department of Production Engineering,
#3Department of Metallurgical Engineering
#PSG College of Technology, Coimbatore, Tamilnadu, India

Abstract

The primary focus of this research was to investigate the parameters that influence the wear rate of a hybrid composite material. The parameters used are the percentages of two reinforcements used, applied weight, and sliding velocity. The methodology involves the production of the hybrid composite utilizing the stir casting process. The ASTM G99 standard is used to evaluate the produced composite materials utilizing a pin-on-disc equipment. The testing settings include changing weights of 10 [N], 20 [N], and 30 [N], as well as sliding velocities of 1 [m.s^{-1}], 2 [m.s^{-1}], and 3 [m.s^{-1}] using RSM technique. The obtained results of wear rate for the composite materials were analyzed for the most influencing parameter and it was found that the sliding velocity is the major factor influencing the wear rate followed by applied load. The weight percentage of cenosphere and weight percentage of MoS_2 are least influencing factors in linear terms and the applied load factor was the only factor having influence in square term also. Interaction plot shows the combinational effect of the weight percentage of cenosphere - weight percentage of MoS_2, weight percentage of MoS_2 – applied load, weight percentage of MoS_2 – sliding velocity and applied load – sliding velocity majorly influencing the wear rate. The weight percentage of cenosphere and MoS_2 found to have a significant influence on the wear behaviour of the composite material even though their percentage contribution is relatively low and the wear rate decreases as the weight percentage of cenosphere and MoS_2 tends to increase.

Key words: Hybrid Metal matrix composites, Aluminium 7075 alloy, cenosphere, MoS_2, Wear Rate, RSM

Introduction

Composite materials are custom-made engineering materials that are tailored for specific applications combining two or more physically distinct materials. The limitations of achieving composite microstructure by self-reinforcement are not conceivable because in general, the performance of ceramic reinforcements in metal matrix composite materials is often linked with continuous fiber reinforcement. Mostly the matrix metal used in the metal matrix composites is Aluminum and its alloys, possessing low density, improved corrosion resistance, high abrasion and wear resistance, high thermal conductivity and high specific modulus which make them relevant in numerous fields such as aeronautical, automobile and marine. The reinforcement is generally powders used in regular metal matrix composites are habitually roughly spherical (equiaxed) between 0.5 to 40 [μm] in diameter, like a grain of sand [1].

The traditional way of reinforcing the MMCs is by using ceramic particulate reinforcements like silicon carbide, alumina, graphite or boron carbide. Sometimes, the unconventional approach of fabricating an MMC rely upon the usage of reinforcement like fly-ash/cenosphere in the metal matrix composite either as a single reinforcement or as one of the reinforcements in the hybrid composites. The Fly-ash/Cenosphere reinforcement possesses less molecular density paralleled with the Aluminum alloy used in the matrix phase of the composites [2]. The less-dense reinforcement diminishes the density of the composite materials which is an advantageous property of composite materials [3]. The fly-ash/cenosphere

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reinforcement benefits in holding the fine grain structure limiting the matrix dislocation movement in the composite [4]. The condition of limiting the matrix dislocation improves the hardness of the composite material [5]. The increment of the cenosphere percentage increments the hardness of the composite [6]. The enhancement of the hardness in the composite material favors the wear resistance of the composite [7]. The wear rate of the composites was appealing when the hardness of the composite improved [8]. The percentage of the fly-ash/cenosphere reinforcement increases, the seizure resistance of the composite [9]. The increase in the fly-ash/cenosphere reinforcement boosts the seizure resistance to a greater extent [10].

Some researchers have utilized solid lubricants like MoS_2 which is also known as metal dichalcogenide belonging to the family of chalcogenide. The wear resistance offered by the Molybdenum Disulphide was due to the formation of a rich film layer on the surface of the composite material in the dry sliding behavior [11]. The Tribo-film layer formed by the MoS_2 reinforcement restricts the plastic deformation of the composite material [12]. The Tribo-layer which forms over the pin evades the direct contact between the Aluminum and the disc [13]. The formation of strain fields around the reinforcement minimizes the wear rate in the composite materials [14]. The MoS_2 reinforcement has a fine dispersion in the matrix which is vital for refining the tribological properties of the composite material because the homogeneous dispersion of the reinforcement in the matrix offers an obstacle to the dislocations in the material structure [15]. The MoS_2 reinforcement also improves the hardness as well as the wear resistance of the composite material [16].

Based on the foremost readings in the metal matrix composites, it was concluded that the study on the tribological characteristics of Aluminum/cenosphere composite material and Aluminum/ MoS_2 composite material was taken to a limited level whereas the reinforcement combinations of cenosphere and MoS_2 in Aluminum metal matrix was not investigated. As an outcome, an effort was made to synthesize AA7075/cenosphere/MoS_2 metal matrix composite materials, and the wear behavior of the composites under non-lubricated sliding wear conditions, as well as the performance of individual process parameters, were investigated using RSM in order to achieve an optimum condition on non-lubricated sliding wear.

Experimental

Development of Composites by Stir-Casting

The aluminium 7075 alloy was chosen as the matrix alloy because it is amongst the most robust aluminium alloys available, making it ideal to be utilized in high-stress circumstances and effective or comparable with most steel alloys in terms of strength attributes. Alloys of aluminium 7075 mainly consist of zinc as the secondary alloying element after aluminium, followed by magnesium, copper, as well as other components. Table 1 indicates the chemical makeup of AA7075.

Table 1. Chemical Composition of AA7075 (weight %).

Al	**Zn**	**Mg**	**Cu**	**Si**
90.91	4.98	1.62	1.55	0.45
Fe	**Ti**	**Mn**	**Ni**	**Pb**
0.19	0.05	0.043	0.008	0.004

The reinforcements utilized in this project were cenosphere and molybdenum disulphide. Cenosphere reinforcements are lightweight, inert hollow spheres. They are generally formed of silica and alumina and are filled with air or inert gas that is produced naturally as a by-product of coal combustion in thermal power plants. It performs well as a binder, and since it is less dense, it is an ideal candidate for use in composite fabrication as one of the filler reinforcements, among other uses. As a secondary reinforcement, a solid lubricant, molybdenum disulphide

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(MoS_2), was used in the development of this material. When it came to the wear test, pins that were manufactured using the stir casting process and machined to Ø8 × 22 [mm], dimensions as shown in Figure 1.

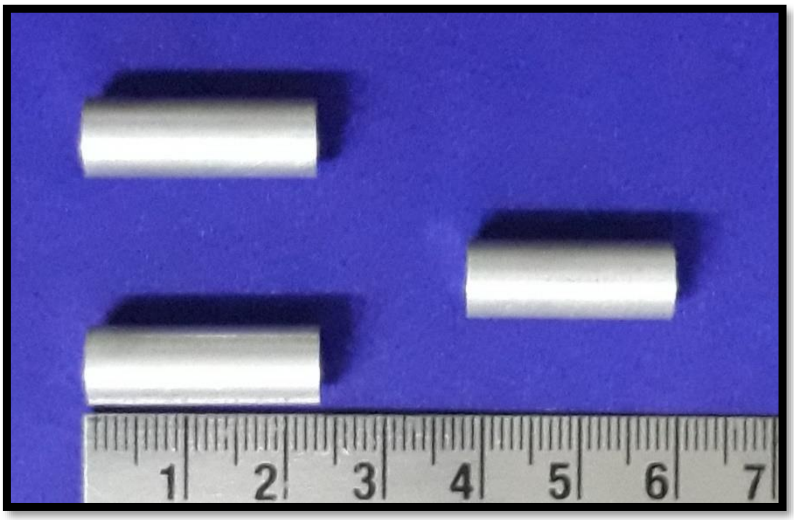

Figure 1. Photographic image of composite pins machined to the dimensions Ø8 mm × 22 mm

Non-Lubricated Wear Test

The experiment was carried out using the Magnum Engineers pin-on-disc equipment system, which was coupled to a data gathering system. The equipment is made up of a setup to hold a stationary pin sliding on a rotating disc of EN32 steel material powered by an electric motor. The pins are polished, cleaned, and dried before being weighed with a 0.0001 [g] precision electronic balance. Wear experiments were run at ambient temperature (28±3°*C*) under the dry sliding condition specified by the ASTM G99 standard [17]. Aside from the various settings, the sliding distance of 1000 [m] was set as a constant. The wear loss was measured using the weight-loss technique of the specimens. The wear loss of the composites in terms of weight loss and volume loss was determined by dividing the observed weight loss by the theoretical density of the composite. The composite's wear rate (WR) was determined using equation (1), wherein ΔV [$g.cm^{-3}$] denotes volume loss.

$$\text{Wear Rate} = \frac{\Delta V}{\text{Sliding Distance}}\left[mm^3 \cdot m^{-1}\right] \qquad (1)$$

Response Surface Methodology

Response Surface Methodology was used as the Design of Experiment technique to investigate the impact of the components in AA7075/cenosphere/MoS_2 on each other (RSM). In addition to the weight percentage of the cenosphere and the weight percentage of MoS_2 in the changing ranges of 0, 2, and 4, other aspects are taken into account. The percentage of reinforcement is limited to 4wt. percent because the tribological characteristics of composites containing reinforcement in excess of 4 percent by weight are inadequate [18]. It is also taken into consideration, the applied load in the range of 10 [N], 20 [N], and 30 [N], as well as the sliding velocity in the range of 1 [$m.s^{-1}$], 2 [$m.s^{-1}$], and 3 [$m.s^{-1}$]. Table 2 shows the levels of each component at which it is present. According to Table 3, the non-lubricated wear tests were carried out for a total of 31 distinct situations that were achieved via the use of Central Composite Design (CCD).

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Table 2. Levels and Factors for the Wear Test.

Factors	Notation	Unit	Factor Levels		
Weight percentage of cenosphere	C	%	0	2	4
Weight percentage of MoS_2	M	%	0	2	4
Load applied	L	N	10	20	30
Sliding Velocity	SV	$m.s^{-1}$	1	2	3

Table 3. Central Composite Design of experiment matrix for a wear test of AA7075/Cenosphere/MoS2 composite material.

Exp. No	C [%]	M [%]	L [N]	SV [$m.s^{-1}$]	Wear Rate $\times 10^{-3}$ [$mm^3.m^{-1}$]
1	0	0	10	1	2.9290
2	0	0	10	3	13.2140
3	0	0	30	1	7.9650
4	0	0	30	3	35.2860
5	0	2	20	2	1.6640
6	0	4	10	1	1.7910
7	0	4	10	3	3.1260
8	0	4	30	1	3.7920
9	0	4	30	3	10.1850
10	2	0	20	2	5.8700
11	2	2	10	2	4.3970
12	2	2	20	1	1.0700
13	2	2	20	2	4.0636
14	2	2	20	2	4.0636
15	2	2	20	2	4.0636
16	2	2	20	2	4.0636
17	2	2	20	2	4.0636
18	2	2	20	2	4.0636
19	2	2	20	2	4.0636
20	2	2	20	3	9.7620
21	2	2	30	2	13.3950
22	2	4	20	2	2.2800
23	4	0	10	1	0.4090
24	4	0	10	3	2.5320
25	4	0	30	1	0.8150
26	4	0	30	3	22.1880
27	4	2	20	2	2.2080
28	4	4	10	1	5.4970
29	4	4	10	3	5.5040
30	4	4	30	1	4.1910
31	4	4	30	3	18.0490

ANOVA and significance testing of the coefficients, and also the fitness of the model, were calculated using Minitab 19 Software to identify the most significant components in linear,

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square, and interaction terms that affected the output response wear rate in the non-lubricated wear condition.

Results and Discussion

Three distinct variables, namely the weight percent cenosphere (C), the weight percent MoS_2 (M), the applied load (L), and the sliding velocity (SV), determine the wear performance of the composite material. Variance analysis using the Response Surface Methodology (RSM) technique provides information on the contribution of the variable factor in terms of linear, squared, and interaction effects. The results of an ANOVA are presented considering only significant terms in Table 4.

Table 4. ANOVA for wear rate $\times 10^{-3}$ [$mm^3.m^{-1}$]

Source	Adj SS	Adj MS	F-Value	P-Value	% Contribution
C	19.14	19.135	4.81	0.040	1.2%
M	75.21	75.207	18.90	0.000	4.7%
L	324.84	324.845	81.65	0.000	20.2%
SV	463.98	463.977	116.63	0.000	28.8%
L*L	165.31	165.310	41.55	0.000	10.3%
C*M	142.78	142.785	35.89	0.000	8.9%
M*L	45.13	45.128	11.34	0.003	2.8%
M*SV	97.56	97.560	24.52	0.000	6.1%
L*SV	190.41	190.406	47.86	0.000	11.8%
Error	83.54	3.978	-	-	-
Lack-of-Fit	83.54	5.570	-	-	-
Pure Error	0.00	0.000	-	-	-
Total	1607.90	-	-	-	-

Influence of Individual Factors on Non-Lubricated Wear

The ANOVA table indicates the performance of individual factors on the wear rate of the hybrid composite material. From Table 4, it was evident that the sliding velocity is the most influencing factor for wear rate having the maximum percentage of contribution up to 28.85 % in linear term whereas there are no traces of sliding velocity in the square term. The significance level of the sliding velocity factor was good since the P-value < 0.05 and from Figure 2, the main effect plot shows that the wear rate surges when sliding velocity rises gradually.

The next factor conditioning was the applied load since the P-value for the applied load was lesser than 0.05 which was significant. Also, the percentage of the contribution of the applied load was 20.2 % in linear terms and in square terms, the percentage of contribution of the factor was 10.3 % which reveals that the applied load plays a major role in the wear rate of the composite material. The ANOVA table also shows that the various components contribute to the wear performance of the composite in the linear term alone. The square term of the components could only be found in the applied load, revealing that the load is perhaps the most important factor impacting the wear rate of the composite. It was noticed from the main effects plot for wear rate (Figure 2) that the wear rate drops slightly for 10 [N] - 20 [N] and then boosts up for 20 [N] - 30 [N].

The weight percentages of the cenosphere and MoS_2 are the least affecting factors, yet they are significant due to their lower P-value (< 0.05) in the linear term. The proportion of contribution for the weight percentage of cenosphere and MoS_2 are 1.2 % and 4.7 %,

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respectively. In the case of the weight proportion of cenosphere and MoS_2, there is no square term impact to the wear rate.

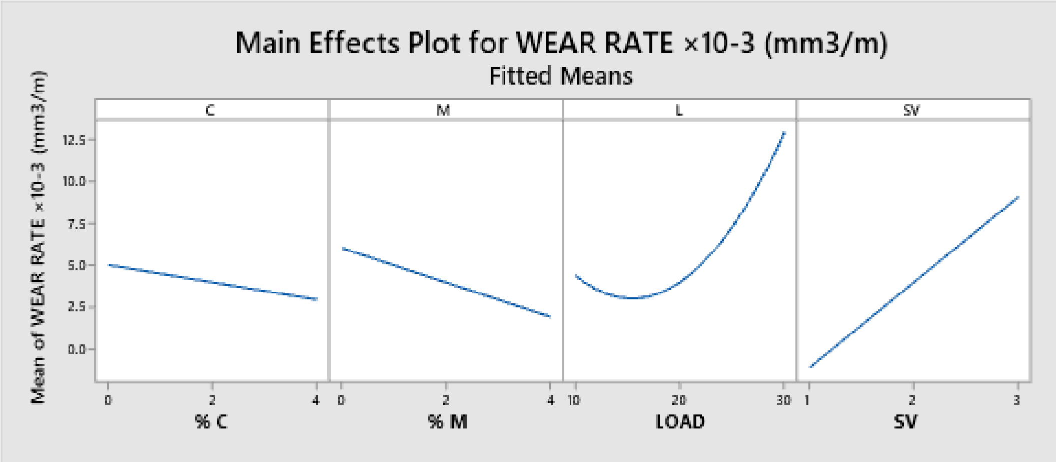

Figure 2. Main Effects Plot wear rate for AA7075/cenosphere/MoS_2 composites

The main effects plot (Figure 2) shows that the wear rate for both the weight percentage of cenosphere and MoS_2 gradually decreases from 0 wt. percent to 4wt.%, indicating that the most affecting factors are the weight percentage of cenosphere and MoS_2, which can be favorable characteristics required for the composite material in controlling the wear rate.

Influence of Interaction among Factors on Non-Lubricated Wear

The interaction plot (Figure 3) showed that the weight percentage of cenosphere - weight percentage of MoS_2, weight percentage of MoS_2 – applied load, weight percentage of MoS_2 – sliding velocity, and applied load – sliding velocity inter-acted. The proportion of contribution for each interaction component was indicated in the ANOVA table (Table 4), with the interaction term of applied load – sliding velocity contributing the most to the wear rate of the composite material (11.8 %). The weight percentage of cenosphere – weight percentage of MoS_2 interaction term has a contribution of 8.9 %, indicating that it is the second most important interaction component after the applied load – sliding velocity interaction term. Along with the aforementioned two interaction factors, the weight percentage of MoS_2 – sliding velocity interaction term contributes 6.1 %, followed by the weight percentage of MoS_2 – applied load interaction term, which contributes 2.8 %. Furthermore, because the P-value was less than 0.05, the significance threshold for all interaction terms was significant. The plotlines in the interaction plot are non-parallel between cenosphere – MoS_2, MoS_2 – applied load, MoS_2 – sliding velocity and applied load – sliding velocity and the interactions between these terms are strong.

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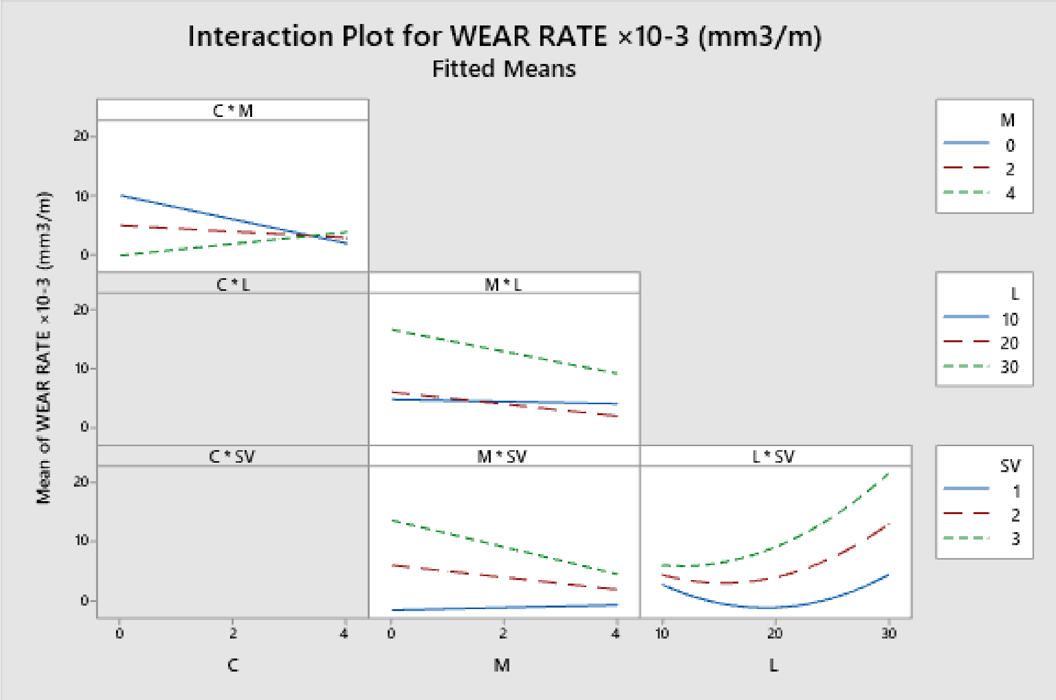

Figure 3. Interaction Plot wear rate for AA7075/cenosphere/MoS_2 composites

Validity of Wear Model and Confirmation Experiments

Table 5 shows the model summary, which shows R^2, the percentage of variation in the response that is explained in the model and is used to determine the wellness of the model that fits the data. The model is appropriate because the R^2 value is nearly 94.80 %. Because the predicted R^2 (80.12 %) is less than the R^2 term, the model is overfitting (94.80 %).

Table 5. Model Summary

S	R-Sq.	R-Sq. (Adj)	R-Sq. (Pred)
1.99456	94.80%	92.58%	80.12%

The optimization of the response obtained was taken into deliberation to acquire the minimal condition for the wear rate by using Response optimization. Table 6 represents the optimized conditions for the minimized condition of wear rate which was 4 wt. % for cenosphere and 0 wt. % of MoS_2, the applied load is optimum for 17.27 [N] and the sliding velocity is 1 [$m.s^{-1}$].

Table 6. Response Optimization Solution

Solution	C	M	L	SV
1	4.00	0.00	17.27	1.00

From the Table 6, it was determined that the predicted optimum combinations for the composite material yield low wear rate and the optimum condition for wear rate of AA7075/cenosphere/MoS_2 composites was represented graphically in Figure 4.

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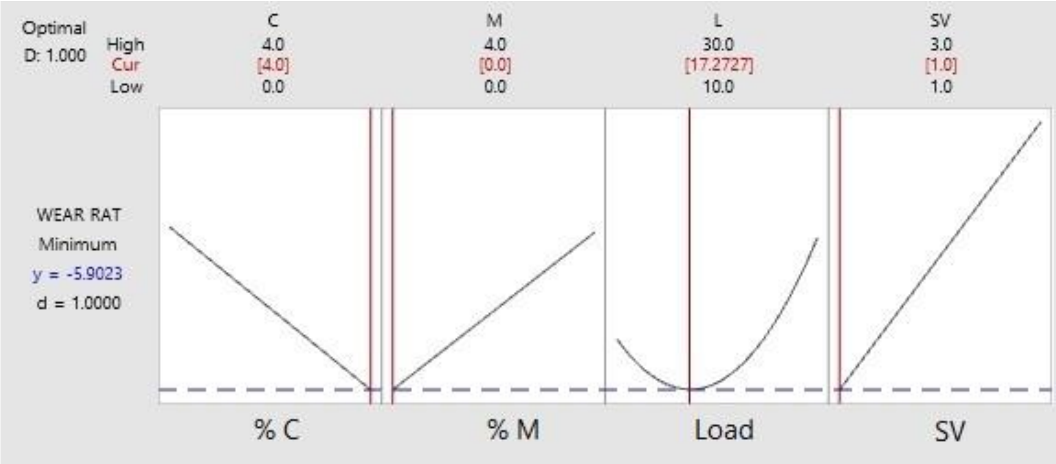

Figure 4. Optimum condition for Wear Rate for the hybrid composites

From Table 6, it was determined that the predicted optimum combinations yield low wear rate and the optimum condition for wear rate of AA7075/cenosphere/MoS_2 composites was represented graphically in Fig. 4.

The confirmation test experiment for the optimum combinations of 4 weight percentage for cenosphere and 0 weight percentage of MoS_2, 17.27 [N], applied load and 1 [$m.s^{-1}$], sliding velocity obtained from Table 6, was conducted. The optimized wear rate was obtained as 0.3680 $\times 10^{-3}$ [$mm^3.m^{-1}$] through the experiment for the combination of the values in uncoded form for the weight percentage of reinforcements, sliding velocity and load. The predicted and experimental values are indicated in Table 7.

Table 7. Confirmation test results for wear rate $\times 10^{-3}$ [$mm^3.m^{-1}$]

Parameter	**C [%]**	**M [%]**	**L [N]**	**SV [m.s-1]**	**Wear Rate Value $\times 10^{-3}$ [$mm^3.m^{-1}$]**	
					Predicted	**Experimental**
Optimum conditions	4	0	20	1	0.3560	0.3680

The SEM image of wear surface (Figure 6.18) for the optimum condition of 4 wt% cenosphere, 0 wt% MoS2, applied load 20 N and sliding velocity 1 m/s was similar to the optimum condition of 2 wt% cenosphere, applied load 20 N and sliding velocity 1 m/s (Figure 6.6) showing mild delamination on the surface of the composite and the wear of the composite implies to be mild abrasive condition with the presence of wear debris.

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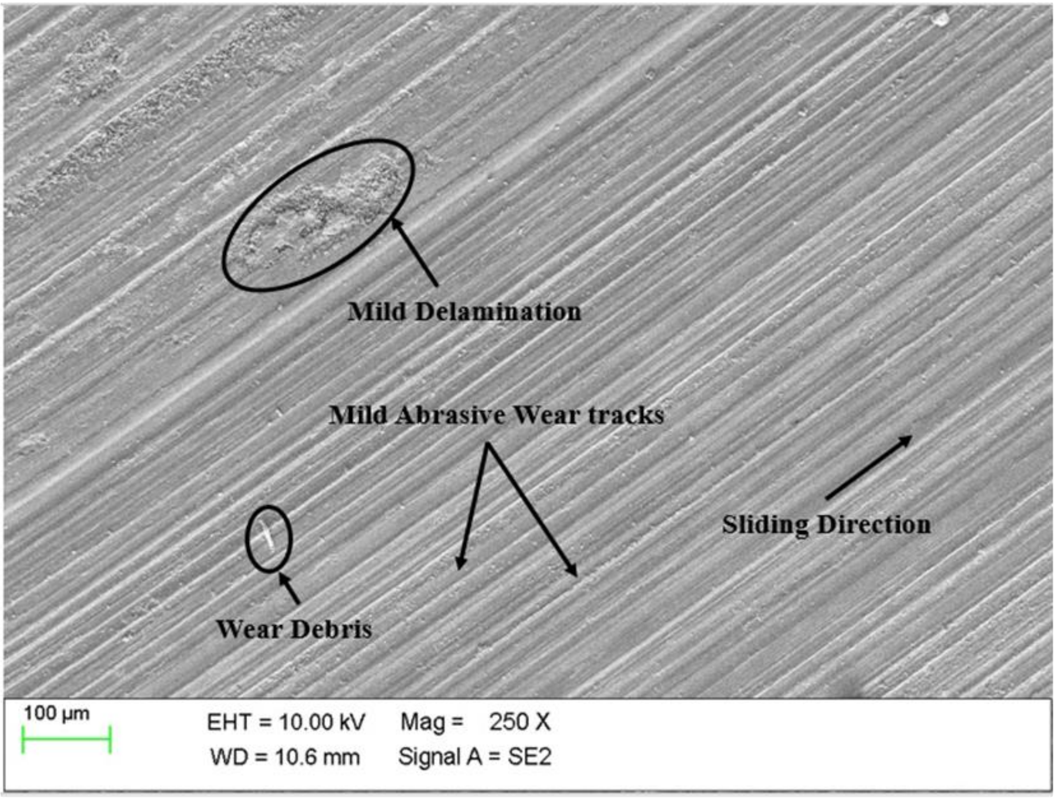

Figure 5. SEM image of worn surface for optimum condition 20 N applied load and 1 m/s for AA7075/cenosphere/MoS_2 composites

Conclusions

The AA7075/cenosphere/MoS_2 composite materials were successfully fabricated by the stir casting process and from the present investigation, the following concluding observations were drawn,

1) The non-lubricated sliding wear characteristics are mainly influenced by the sliding velocity. It was evident that the wear rate of the composites increased with the increase of the sliding velocity.

2) Succeeding the sliding velocity, applied load favors the wear rate of the hybrid composite material but the weight percentage of cenosphere and MoS_2 are the factors that affect the wear rate of the hybrid composite material.

3) Based on the ANOVA table, the significance level of the factors - weight percentage of cenosphere, weight percentage of MoS_2, applied load and sliding velocity are good in linear, square and interaction terms.

4) The percentage of contribution for the wear rate of the hybrid composite was 28.85 % of sliding velocity pursued by 20.2 % of applied load, 4.7 % of weight percentage of MoS_2 and 1.2 % of weight percentage of cenosphere employing a noteworthy influence on the wear rate of the composites in linear terms.

5) In square terms, the applied load (10.3 %) alone makes an impact on the wear rate.

6) The interaction terms of applied load – sliding velocity shows a major contribution of nearly 11.8 % over the wear rate of the hybrid composite material followed by 8.9 % of weight percentage of cenosphere - weight percentage of MoS_2, 6.1 % of weight percentage of MoS_2 - sliding velocity and 2.8 % of weight percentage of MoS_2 – applied load.

7) The optimum combination for the wear rate of the composite material was attained at 17.27 [N] applied load, 1 [$m.s^{-1}$] sliding speed, and 4 wt. % cenosphere percentage.

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