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RESEARCH

Studies on Adhesive Wear Characteristics of Heat Treated Aluminium LM25/AlB_2 Composites

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A B S T R A C T

The main aim of this study was to determine the adhesive wear characteristics of heat treated LM 25/AlB_2 metal matrix composites fabricated using liquid metallurgy route. The composite samples were solutionized at 525 °C and then water quenched. Aging was done at different temperatures (160 °C, 175 °C, 200 °C and 250 °C) for different aging time (4 hrs, 6 hrs, and 8 hrs). Brinell hardness tester was used to evaluate the hardness of all aged samples and maximum hardness (82 HRB) was observed in the sample aged for 6 hours at 250°C . Those heat treated specimens were taken for further experimentation on wear characteristics. Pin-on-disc tribometer was used to analyse the dry sliding wear characteristics and the experiments were conducted based on Taguchi's L_{16} orthogonal array by varying the process parameters of load (10 N, 20 N, 30 N and 40 N), sliding distance (400 m, 800 m, 1200 m and 1600 m) and sliding velocity (1 m/s, 2 m/s, 3 m/s and 4 m/s) for four levels. The dependence of wear rate on various parameters was found out using ANOVA and S/N ratio. The experimental result shows that sliding velocity (56.6 %) influences more on wear rate followed by load (23.09 %) and sliding distance (6.02 %). The regression equation was developed and the confirmatory result shows less error. The worn surfaces were analysed using Scanning Electron Microscope and severe delamination at the sliding velocity of 1m/s was found.

1. INTRODUCTION

Nowadays, the applications of Metal Matrix Composites (MMCs) are more because of their good mechanical properties like high specific strength, high specific stiffness and high wear resistance. MMCs are mostly used in automobile industry because of its high strength to weight ratio and is also used for some industrial applications [1,2]. MMCs are mostly preferred to be reinforced with particles than fibres to have good wear resistance [3]. Aluminium is mostly used as a matrix material because of its good mechanical properties, high strength to weight ratio and cost effectiveness. Aluminium Metal Matrix Composites (AMMCs) are mainly used for turbine blades, pistons, cylinder blocks, brake linings and clutches [4,5]. Addition of reinforcement into the matrix element increases the stiffness, specific strength, wear, creep and fatigue properties [6].

There are many techniques to fabricate MMCs such as semi solid methods, deposition processes, liquid state fabrication which consists of stir casting, squeeze casting, compo casting, ultrasonic casting, spray deposition and solid state fabrication which consists of powder metallurgy, diffusion bonding, vapour deposition technique and friction stir process. Major problems found during the fabrication are agglomeration, improper bonding and improper distribution of reinforcement in matrix element. Hence, a proper casting technique should be used to fabricate MMCs to avoid those major defects [7]. Stir casting method is found to be the most economical and simple way to fabricate AMMCs in order to achieve homogenous dispersion of reinforcement [8]. Researchers also have used stir casting technique successfully to fabricate aluminium composites by reinforcing the particulates like Silicon Carbide (SiC), Alumina (Al_2O_3) and graphite [9].

Heat treatment enhances the surface properties of materials. The hardness and impact strength of AMMCs increases by heat treatment process [10]. Heat treatment significantly affects the microstructure by relieving the internal stress and refines the grain structure of AMMCs [11]. The frit particulates reinforced with Aluminium 6061 is heat treated and the increase in hardness is found upto the aging time of 6 hrs and decrease in hardness is seen with further increase in aging time [12]. Aluminium reinforced with Boron Carbide (B_4C) when subjected to heat treatment has more hardness than the non-heat treated composite [13].

Adhesive wear occurs due to the relative motion between two materials where the plastic deformation is attained when an applied stress exceeds a critical value [14]. The factors which influence the adhesive wear of AMMCs are bond strength, particle size of reinforcement (SiC) and inter particle spacing [15]. Researchers found that the parameters which affect the adhesive wear rate of Al-Si10Mg reinforced with alumina and graphite is load, sliding distance and sliding velocity. The wear rate can be controlled by controlling the aforementioned parameters [16]. In Al-Si alloys and aluminium based MMCs, the increase in hardness increases the wear resistance [17].

Design of Experiments (DOE) is a systematic method to determine the relationship between factors affecting a process and the output of that process. In other words, it is used to find cause-and-effect relationships. The Taguchi method is the best optimization process to achieve high quality results without increase in cost [18]. LM6Al-7.5wt.% SiC MMCs is successfully developed using L_{27} Taguchi orthogonal array and is found that sliding distance has more impact on wear rate followed by load and sliding speed [19]. Taguchi method uses the different orthogonal arrays to increase the effect of controllable parameters and to decrease the effect of uncontrollable parameters. This orthogonal array depends on the number of parameters and levels used in the experiment [20].

Based on the above literature, it is observed that the work done by the researchers is not much on Al/AlB_2 composites. Hence, an effort is taken to study the tribological behaviour of LM25 aluminium reinforced with AlB_2 and also the change in properties through heat treatment process.

2. SELECTION OF MATERIAL

The selected base matrix is LM 25 aluminium with the density of 2.68 g/cm^3. LM 25 has an excellent castability and is also used where higher corrosive resistance is an important consideration. It has good mechanical properties and higher strength. Hence, this alloy finds its applications in automotive industry where it is used for making cylinder heads, cylinder blocks and wheels. In order to improve its wear characteristics, AlB_2 (45 μm) is selected as the reinforcement (10 wt.%) with density of 3.19 g/cm^3. The melting point and specific heat capacity of AlB_2 is 1655 °C and 43.6 J/mol K respectively. The application of AlB_2 includes usage in grinding and polishing tools in the place of diamond dust.

3. SYNTHESIS OF COMPOSITE

Stir casting method is found to be the simple and economical way to fabricate the AMMCs. Two steps involved in the stir casting method are melting of aluminium alloy and mixing of reinforcement with molten matrix. Initially LM 25 is cut into many pieces and placed in a graphite crucible. Then it is melted in a furnace by heating it to a temperature above 760 °C. In order to have good wettability, AlB_2 is pre heated to a temperature of 300 °C. Then the molten LM 25 and preheated AlB_2 are stirred together with the speed of 310 rpm for 5 minutes with the aid of stirrer attached along with the furnace to achieve homogeneous dispersion of reinforcement particles over matrix metal. Then it is allowed to solidify after pouring it in a preheated mould of 300 °C. The composite samples are then machined (30*8*8 mm) from the cast part for further heat treatment. The edges of each specimen are grinded to remove the blurs.

4. HEAT TREATMENT PROCESS

The heat treatment process involves three different phases called solution treatment, quenching and artificial aging. Initially the composite is heated to a temperature of 525 °C for 8 hrs until the solute elements of alloy are dissolved completely in the LM 25 solid solutions. Then the specimens are water quenched and are aged at the temperature 160 °C, 175 °C, 200 °C and 250 °C for an aging time of 4 hrs, 6 hrs and 8 hrs. Then those specimens are cooled naturally.

5. ADHESIVE WEAR TEST

Wear can be analysed by various methods such as abrasion wear, adhesive wear and wear test by ferrography method. Dry sliding wear test is popular among these techniques [21]. The sliding wear characteristics of the heat treated AMMC having highest hardness is studied at room temperature utilizing pin-on-disc tribometer in dry condition. The L_{16} orthogonal array is used to carry out experiments. This tribometer consists of a rotating disc which has varying speed from 50 rpm to 2000 rpm. This also has a stationary holder at one end to hold the composite specimen and the other end has a fixed arm with pulley where loads are mounted. The force provided by the load applied to the pulley maintained the contact between rotating disc and composite specimen. The rotating disc is cleaned using emery sheets made from SiC. Edges of the composite specimen is also cleaned and fixed correctly so that the entire surface of composite specimen is slided over the rotating disc. Weight of each specimen is noted before and after wear test using electronic weighing machine with an accuracy of 0.1 mg. The experiments are conducted with a constant track diameter of 90 mm. The various parameters involved in this experiment are listed along with their levels in Table 1.

Table 1. Process parameters and their levels

Level	Load (N)	Velocity (m/s)	Sliding Distance (m)
1	10	1	400
2	20	2	800
3	30	3	1200
4	40	4	1600

6. RESULTS AND DISCUSSION

Hardness measurement results, Signal-to-Noise ratio analysis, Analysis of Variance (ANOVA) and the Scanning Electron Microscope analysis are discussed in detail in the following sub sections.

6.1 Hardness Measurement

The hardness test is carried out on all heat treated specimens using Brinell hardness tester. It has a ball indenter of 3 mm diameter and 100 Kgf of load is applied to the composite specimens. Three readings are taken for each specimen and the value given is the average of those three readings. Hardness values of those composites obtained for different aging time and temperature are shown in Table 2. The highest hardness achieved by the specimen is 82 HRB at the aging temperature of 250°C with aging time of 6 hrs. Hence these composite samples with higher hardness are considered for further experimental work.

Table 2. Hardness values with aging temperature and time.

S. No	Temperature (°C)	Time (hrs)	Hardness (HRB)
1	160	4	28
2	160	6	36
3	160	8	37
4	175	4	47
5	175	6	49
6	175	8	53
7	200	4	50
8	200	6	60
9	200	8	76
10	250	4	80
11	250	6	82
12	250	8	80

6.2 Tribological Behaviour

The wear rate is calculated for the heat treated composite for all 16 experiments obtained from L_{16} orthogonal array and the results are shown in Table 3.

Table 3. Experimental results.

S. No	Sliding Velocity (m/s)	Load (N)	Sliding Distance (m)	Wear Rate (mm^3/m)
1	1	10	400	0.0027460
2	1	20	800	0.0022880
3	1	30	1200	0.0036900
4	1	40	1600	0.0038900
5	2	10	800	0.0013730
6	2	20	400	0.0018300
7	2	30	1600	0.0022880
8	2	40	1200	0.0021350
9	3	10	1200	0.0006127
10	3	20	1600	0.0009154
11	3	30	400	0.0018300
12	3	40	800	0.0028850
13	4	10	1600	0.0019770
14	4	20	1200	0.0022560
15	4	30	800	0.0026200
16	4	40	400	0.0030600

6.3 Signal - to - Noise Ratio Analysis

The Minitab software is used to develop the Signal -to - Noise (S/N) ratios for the parameters which influences the wear rate and 'smaller-the-better' characteristic is selected for this analysis. Table 4 shows the S/N response table for parameters such as sliding velocity, load and sliding distance.

Table 4. Response table for S/N Ratio.

Level	Velocity (m/s)	Load (N)	Sliding Distance (m)
1	45.85	59.21	51.85
2	54.56	56.13	52.21
3	57.65	51.68	56.26
4	57.06	48.42	55.11
Delta	11.80	10.79	4.41
Rank	1	2	3

The parameter which influences more on wear rate is determined from the delta value. Delta value is given by the difference between the peak S/N ratio value and the lowest S/N ratio value of the parameter. The parameter having higher delta value influences more on wear rate. The impact of sliding velocity is found high followed by load and sliding distance.

6.4 Influence of Parameters on Wear Rate

A set of experiments are conducted as per L_{16} orthogonal array to observe the effect of sliding velocity, load and sliding distance on wear rate at varying level of influence. The graphs plotted for wear rate and the S/N ratios are shown in Fig. 1. The optimum values to achieve minimum wear rate are, sliding velocity of 3 m/s, load of 10 N and sliding distance of 1200 m. The variation for wear rate at various levels of each parameter is shown in Fig. 2.

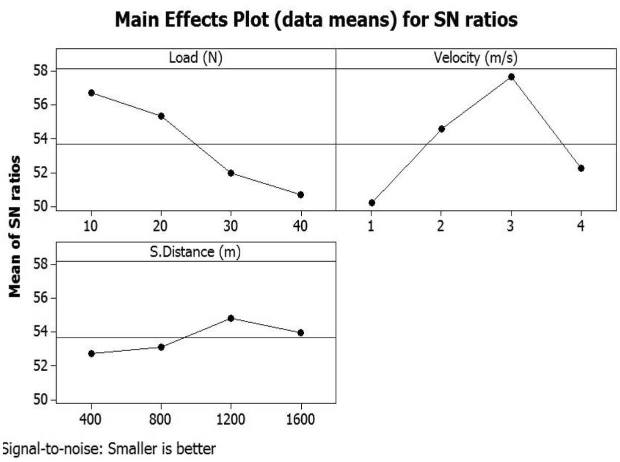


Fig. 1. Main Effect plot for wear rate.

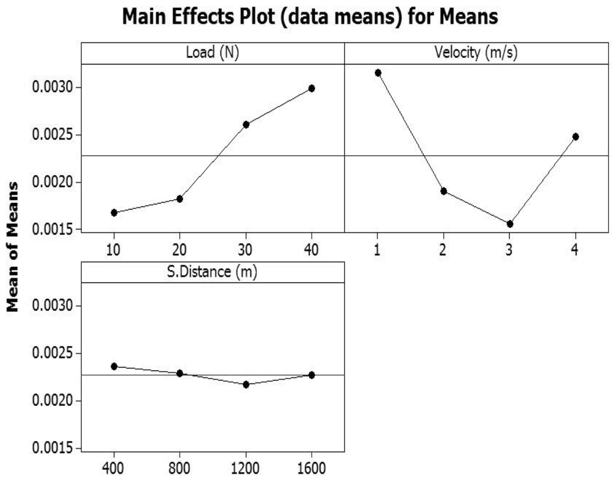


Fig. 2. Main Effect plot for Means.

6.5 Effect of Load on Wear Rate

The plot for wear rate against different loads (10 N, 20 N, 30 N, and 40 N) is shown in Fig. 2. From this figure, increase in wear rate is observed when load increases from 10 N to 40 N and similar trend is observed [4]. This increase in wear of the composite is due to the increase in the contact pressure between the interface of specimen and counter face. When the load increases equally, gradual increase in wear is observed. For a load of 10 N, the wear of the composite is mild. This is due to the rubbing action produced between the composite and the sliding surface. When the range of load is 20-30 N, the wear is found to be high and this is due to the adhesive action. At this range, the contact pressure between composite surface and counter face is high results in higher wear. When the load is 40 N, wear increases due to the ploughing action.

6.6 Effect of Sliding Velocity on Wear Rate

From the Figure 2, decrease and increase in wear rate is observed when the sliding velocity varies from 1 m/s to 4 m/s. When the velocity is 1 m/s, the wear of the composite is higher due to severe delamination of asperities on composite surface developed by sliding action. Wear rate is found to be decreasing when the sliding velocity varies from 2 m/s to 3 m/s where similar slope is seen in another study [4]. Transfer of material takes place at this condition due to repetitive sliding action and in turn forms a layer of wear debris. Simultaneously, oxide layer is formed due to rise in temperature at the interface, which in turn reduces the wear rate. When the sliding velocity is 4 m/s, increase in wear rate is observed due to the weak interface bond. At this velocity, the interface temperature becomes high which made the material to get softened. Hence, the interfacial bonding strength becomes weak and the wear debris particles get detached by sliding action. The wear rate is increased due to this detachment of wear debris particles.

6.7 Effect of Sliding Distance on Wear Rate

Decrease in wear rate from 400 m to 1200 m and slight increase in wear rate up to 1600 m is observed from Figure 2. At a sliding distance of 400 m, the wear rate is observed to be higher because, the hard asperities protruding from composite surface gets in contact with counter face and fractured due to the sliding action. When sliding distance increases, hard asperities from the composite surface gets smoothened and uniform contact between the composite surface and the counter face is obtained. Hence decrease in wear rate is found at the sliding distance of 800 m and 1200 m and similar trend is observed [16]. When sliding distance reaches 1600 m, the temperature of the composite surface becomes more and this makes the composite soft. When the softer material slides over a harder material, wear rate increases. So the wear rate is found to be more for the sliding distance of 1600 m.

6.8 Analysis of Variance for Wear Rate

The ANOVA is used to find out the parameter which affects the performance characteristics and the ANOVA table is shown in Table 5.

Table 5. Analysis of Variance for wear rate.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Percentage
Sliding Velocity	3	0.0000395	0.0000395	0.0000132	8.05	0.016	56.67
Load	3	0.0000161	0.0000161	0.0000054	3.28	0.100	23.09
Sliding Distance	3	0.0000042	0.0000042	0.0000014	0.86	0.512	6.02
Error	6	0.0000098	0.0000098	0.0000016			14.06
Total	15	0.0000697					

Significance level of 5 % is carried out for this analysis. P value of sliding velocity from the table is less than 0.05. Hence the major influencing parameter on wear rate is found to be the sliding velocity (56.67 %), followed by load (23.09 %) and sliding distance (6.02 %).

6.9 Linear regression analysis

The linear regression equation is developed to the influencing parameters such as sliding velocity, load and sliding distance using Minitab software. The regression equation for the wear rate is given below:

$$\text{Wear rate} = 0.00194 - 0.000691\,V + 0.000085\,L + 0.000001\,S.D$$

Where V is the sliding velocity (m/s), L is the load (N) and S.D is the sliding distance (m).

The wear behaviour is inferred by the sign on the equation. The parameter prefixed with the positive sign denotes that the wear rate increases when it increases and the negative sign denotes that the wear rate decreases as the level increases. The confirmation test is performed with the parameters other than the selected parameters as shown in Table 6.

Table 6. Parameters and levels selected for confirmation experiment.

S.No	Sliding Velocity (m/s)	Load (N)	Sliding Distance (m)
1	1.2	15	600
2	2.5	25	1000
3	3.7	35	1300

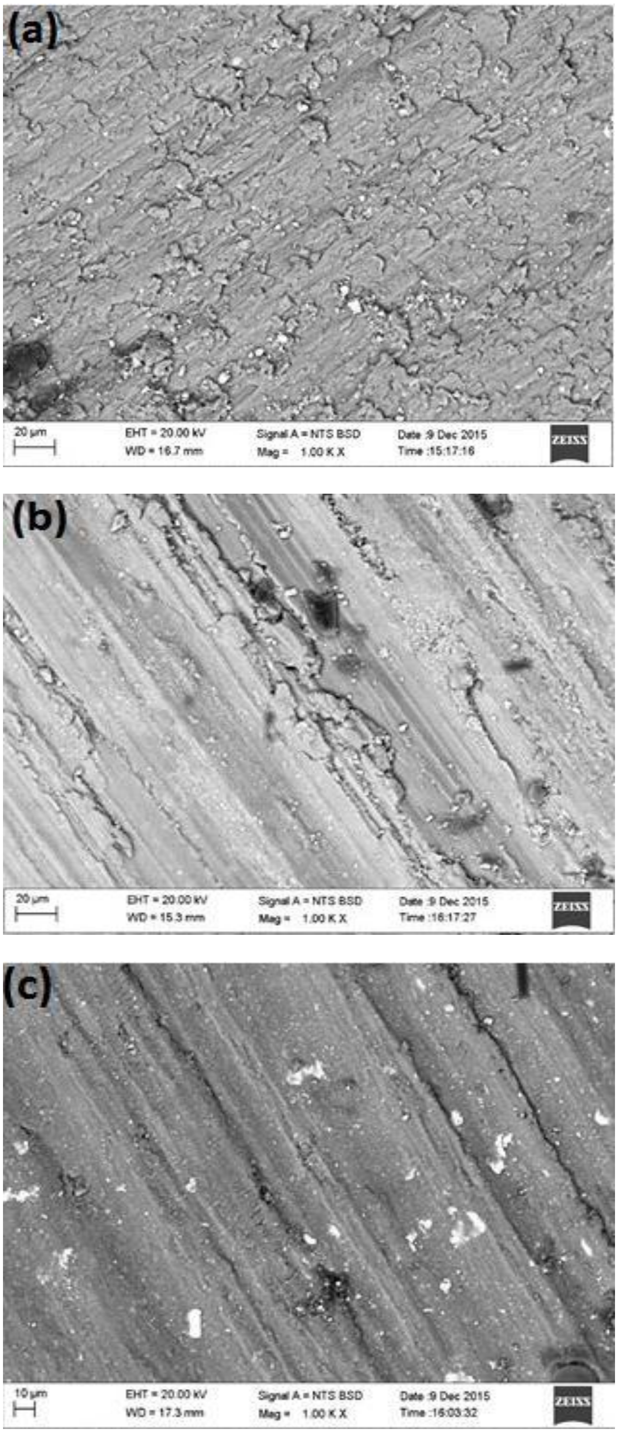
The wear test is conducted for the preferred levels. Then the result obtained from the wear test is compared with the regression wear rate. The results obtained from the wear test and the regression equations are shown in the Table 7. It is observed that the error obtained is less than 10 %. Hence, the developed model has higher efficiency to predict the wear behaviour.

Table 7. Results of confirmation experiment and correlation analysis.

S.No	Experimental wear rate (mm^3/m)	Regression wear rate (mm^3/m)	Error (%)
1	0.0027543	0.0029858	7.75
2	0.0031355	0.0033375	7.06
3	0.0033154	0.0036583	9.38

6.10 Scanning Electron Microscope Analysis

Scanning Electron Microscope (SEM) analysis is carried out for the worn surface to analyse the effect of sliding velocity and load on the wear rate during the tribological testing as these parameters have maximum impact on wear rate. Figures 3(a-c) shows SEM images of the worn out surface of composite specimen subjected to three different sliding velocities (1 m/s, 2 m/s and 4 m/s) with a load of 10 N.



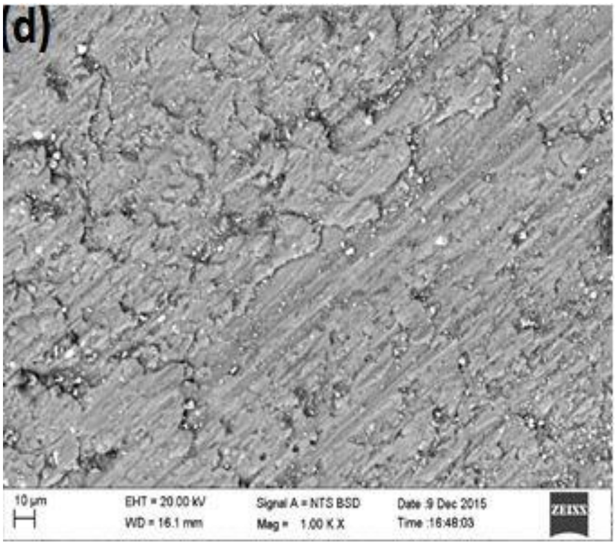


Fig. 3. Worn out surface analysis at various conditions a) L = 10N, V = 1m/s, S.D = 400m b) L = 10N, V = 2m/s, S.D = 800m c) L = 10N, V = 4m/s, S.D = 1600m d) L = 30N, V = 1m/s, S.D = 1200m.

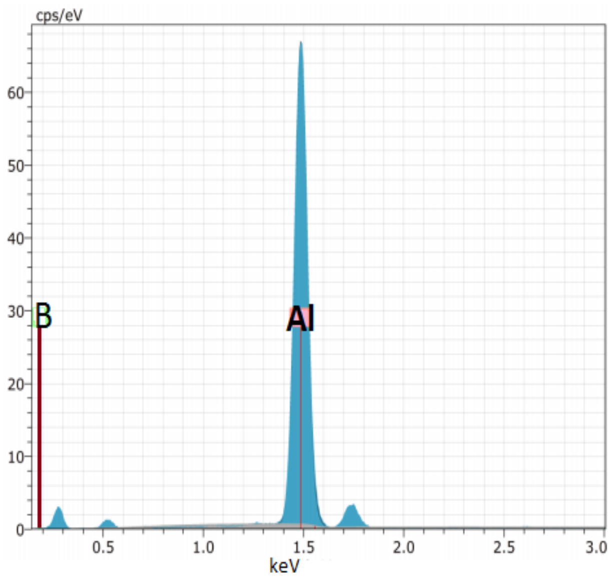


Figure 4. EDS analysis of LM25/AlB_2.

The Figure 3(a) has significant amount of grooves on the pin due to the ploughing effect of the disc and also more number of reinforcement particles are seen on the surface which is ensured by EDS analysis (Fig. 4). The severe delamination makes more material removal and the above observations are used to conclude that the wear rate is high for the sliding velocity of 1 m/s. Then it is observed from the Fig. 3(b-c) that the number of grooves in the worn surfaces is less which indicates that the wear rate decreases with the increase in sliding velocity of the disc. The Figure 3(d) is the worn out surface of the specimen which is tested under increased load of 30 N. Comparison is made between Fig. 3(a) and Fig. 3(d) to determine the effect of load on wear rate with constant sliding velocity (1 m/s). More grooves and reinforcement particles are observed in the Fig. 3(d) indicating the increase of wear rate by increase of load for the same sliding velocity.

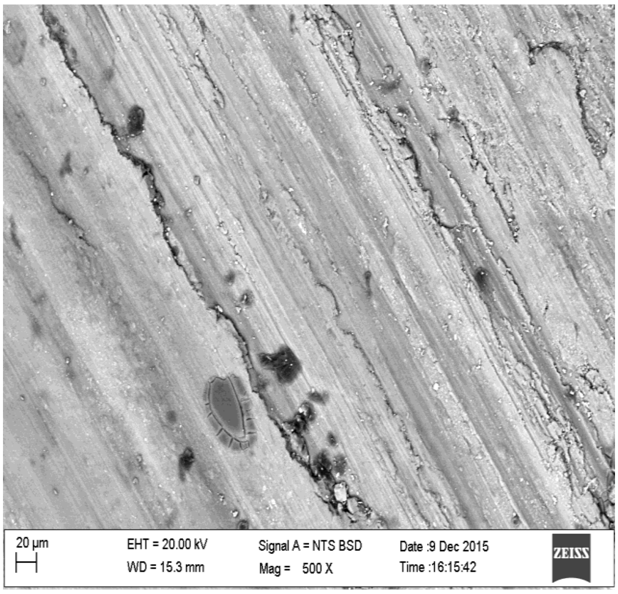


Figure 5. Worn out surface at optimum condition.

The worn surface at optimum condition (V = 2 m/s, L = 10 N, S.D = 800 m) is shown in Fig. 5 and observed shallow scratches, minimum grooves and delamination which reveals less wear rate. This is due the presence of hard reinforcement particles at the composite which bears the load impacted on the matrix surface.

7. CONCLUSION

The adhesive wear test using pin-on-disc tribometer was successfully carried out on heat treated composite specimens. Taguchi's design was used to examine the wear rate. From the S/N ratio analysis and the ANOVA table, it was observed that sliding velocity (56.6 %) had more impact on wear rate followed by load (23.09 %) and sliding distance (6.02 %). The regression equation was developed and it was validated with the confirmatory results. More delamination was observed on the worn surface at the sliding velocity of 1m/s. The optimum condition at V=3 m/s, L=10 N and S.D=1200 m was found to have less wear rate. Hence this composite can be used in automotive and aerospace applications where wear becomes major consideration.

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