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RESEARCH

Wear Response of Aluminium 6061 Composite Reinforced with Red Mud at Elevated Temperature

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A B S T R A C T

The present work is focused on the investigations on dry sliding wear behaviour of aluminium metal matrix composite at room and elevated temperature. Aluminium metal matrix composites reinforced with red mud are prepared by stir casting method. The experiments are planned using Taguchi technique. An orthogonal array, analysis of variance and signal to noise ratio are used to check the influence of wear parameters like temperature, percentage of reinforcement, mesh size, load, sliding distance and sliding speed on dry sliding wear of composites. The optimal testing parameters are found and their values are calculated which are then compared with predicted values. A reasonable agreement is found between predicted and actual values. The model prepared in the present work can be effectively used to predict the specific wear rate of the composites.

1. INTRODUCTION

Aluminium metal matrix composites (MMCs) are almost used in all engineering industry since they possess low density and high specific strength. Aluminium 6061 has higher resistance towards corrosion and therefore is used in industries like marine, automobile and construction etc. [1]. Automobile applications specially engine parts pushed researchers for improvement of MMCs. In MMCs wear resistance properties are most significant for improvement [2-4]. At room temperature, Aluminium possess excellent properties, however it shows poor high temperature behaviour. In order to explore this behaviour of aluminium, it is reinforced with ceramic particles. Conventional reinforcements like SiC, Al_2O_3, TiC etc are expensive [5,6] and thus, the demand for less expensive reinforcements lead to interest towards red mud, Rice Husk Ash (RHA), Fly Ash [7-10] which are waste of one or the another industry. Red mud is industrial waste obtained from Bayer's process that contains different constituents like Al_2O_3, Fe_2O_3, TiO_2, and Na_2O etc. and can be considered as a possible reinforcement in composite for wear resistant application [7]. Particle composites also have higher heat and wear resistance properties as per findings [11,12]. Wear of materials is the most vital yet least focused parts of tribology. Wear of a material is the surface harm caused due to relative movement between the two surfaces. It might be in form of loss of material, micro-cracks or localized plastic deformation. Wear results in productivity reduction, loss of power, higher oil consumption and early part replacement. Wear is a framework property, and any variation in load, speed or working conditions will change wear rate [13-15]. It is reported in literature that the presence of oxides on contact surface can reduce wear rates by reducing or avoiding direct metal contact. These oxides may be present as fine wear debris particles on the surface and at higher temperatures, a smoothly-burnished top layer is formed with a glaze on surface of the compacted particles, which results less friction between the contact surfaces and rate of wear becomes very low [18]. Literature also shows that the addition of harder particles improves the wear resistance of aluminium matrix composite [19]. Oxygen peaks are seen on the surface after wear test of Aluminium and this shows the formation of oxide layer [20].

1.1 Taguchi technique

Complete experimental design of experiments requires lot of time and money. Factorial design can significantly reduce the time and number of experiments however it might not contain the best design point. To solve this problem, Taguchi's design technique has been used by using appropriate orthogonal array. The Taguchi Technique is an accurate, simple method to plan the experiments with reduction in expenses and improvement in quality. Taguchi method has been used in present work to determine the order in which process parameter affects the specific wear rate [5,21-25].

The aim of the present study is, therefore, to investigate the wear behaviour of aluminium 6061 composites reinforced with red mud at elevated and room temperature. The composite is fabricated by stir casting. A L_{18} orthogonal array, signal to noise ratio, ANOVA (analysis of variance) have been applied to study performance characteristics of composites parameters (percentage, mesh size, temperature, load, sliding distance and speed) with respect to wear rate of composite.

2. MATERIAL AND METHODS

2.1 Materials

Red mud has been procured from Hindalco Industries Limited plant which is situated at Renukoot, Uttar Pradesh, India. Aluminium 6061 is used in a matrix while red mud is used as reinforcement with varying average mesh size of 200, 100 and 80. The percentages of red mud used as reinforcement are 8 %, 12 % and 16 %.

2.2 Fabrication of composite

Aluminium 6061 metal matrix composites has been fabricated by stir casting method [1]. Aluminium has been heated to 1173 K to increase its fluidity. Red mud particles have been preheated to 673 K before injecting into molten aluminium. Mechanical stirrer has been used for mixing of red mud particles in molten aluminium. Before adding the red mud particles, magnesium (1 % by weight) has been added in the molten aluminium to increase the wetablity of red mud particles with aluminium 6061 [16]. After the proper mixing, the molten mixture has been poured into the mild steel moulds. Samples for conducting wear experiments have been fabricated by machining of obtained castings on Lathe machine having 10mm diameter and 30 mm length. Solutionizing heat treatment of the fabricated samples has been done by heating the samples at 798 K for 120 minutes followed by water quenching.

2.3 Friction and wear test

The tribological test of aluminium 6061 reinforced with red mud is carried out at ambient temperature (305 ±5 K) and at elevated temperature (473 K) using a pin on disc wear testing machine with pin on disc contact geometry as shown in Fig. 1.

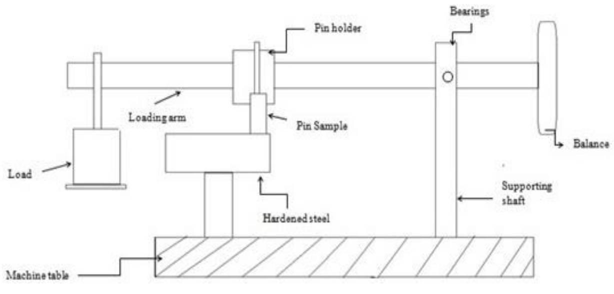


Fig. 1. Schematic diagram of experimental setup of pin on disc wear machine.

The diameter and length of the specimen used for wear test has been 10mm and 30mm, respectively. Before conducting the wear test, the contact surfaces of the specimen have been grounded with emry paper of grit size (80, 120, 220, 320, 400, 600, 1000, 1500 and 2000) to achieve an average surface roughness (Ra) less than 800 nm. After grounding, the surface has been polished by using 'brite-o' solution. The surface of specimens has been cleaned with acetone before fitted on machine. High precision digital microbalance with least count of 0.0001 g is used for weighing the sample before and after the wear test.

2.4 Experimental design

To study the wear behaviour six parameters have been chosen after considering the feasibility and economical limitations. Three levels of parameters have been selected for observing maximum possible variation and to reduce the error. A standard Taguchi L_{18} (1^2, 5^3) orthogonal array has been chosen to check the influence of the parameter on specific wear rate of composites. L_{18} array has been selected by considering max degree of freedom of the parameters at three levels. The factors and level of control parameters are shown in Table 1.

Table 1 Control factors and their levels.

Parameter	Code	Level-1	Level-2	Level-3
Temperature (K)	A	303±5	473	
Percentage of Red-mud	B	16	12	8
Reinforcement Size (Mesh)	C	200	100	80
Load (kgf)	D	1	2	3
Sliding Distance (m)	E	2000	3000	4000
Sliding speed (m/s)	F	1.27	1.90	2.54

A total of six factors have been used. One factor of two levels and other five factors of three levels are used. In the Taguchi technique, the test results are changed into a signal to noise (S/N) ratio. Taguchi use S/N ratio to gauge the quality attributes deviating from the desired values. There are three classes of the S/N ratio value which can be used in the investigation are i.e. smaller the better, larger the better and nominal the better. In this study, the smaller the better approach has been taken because of examining the wear resistance of the MMCs as our priority is to minimize the response. The S/N ratio for every level of testing parameters was figured taking into account the S/N examination. In addition, a factual investigation of change has been performed to see which test parameters are factually significant. With S/N ratio and ANOVA examinations, the ideal combination of the testing parameters could be anticipated for a 95 % certainty level. To get the insight about the wear behaviour after completing total experiment wear surfaces were analyzed by scanning electron microscopy for both elevated and room temperature samples.

3. THEORY AND CALCULATION

In S/N analysis, the greater the S/N, the better is the experimental results. After analysis of S/N ratio ANOVA is calculated. ANOVA gives the significance of parameters and informs us about the percentage of contribution of the parameters on output response. At last, confirmation test is done which later on, compared with theoretical results. During the work, total of 18 experiments has been performed with repeatability. The specific wear rate (SWR) has been calculated by the equation:

$$SWR = V/LqD \quad (1)$$

where, q is the density of material (g/cm^3), V is the weight loss (gm) and D is the sliding distance (m). Specific wear rate (SWR) (mm^3/Nm), where L is the applied load (N) [16 17]. The S/N ratio is evaluated by the equation [23]:

$$N = -10 \ \mathrm{Log}_{10} \ [\text{mean of sum of squares of measured data}] \quad (2)$$

4. RESULTS AND DISCUSSION

4.1 Microstructure

Scanning electron microscopy (SEM) has been used for analysis of aluminium 6061 composite with different percentage of red mud is shown in Figs. 2-4.

The SEM results show us that the distribution of red mud in the composite has been fairly homogeneous. Some agglomeration of reinforcement is found in 200 mesh size i.e. 74 micron reinforced composite. The agglomeration caused may be due to small size of the reinforcement. Examination of figures and Energy dispersive X-ray spectroscopy (EDS) analysis confirms the presence of red mud constituent elements in the composite. EDS images of specimens have been shown in Figs. 5-7.

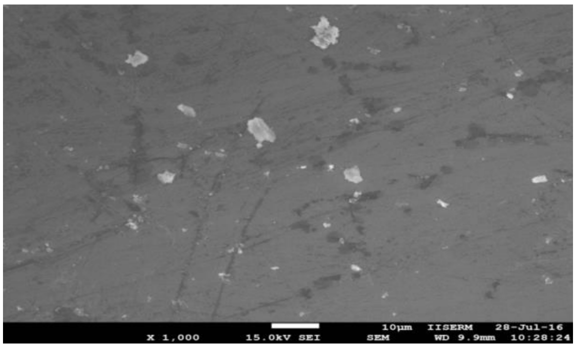


Fig. 2. SEM image of MMC at 8 % reinforcement and 80 mesh size.

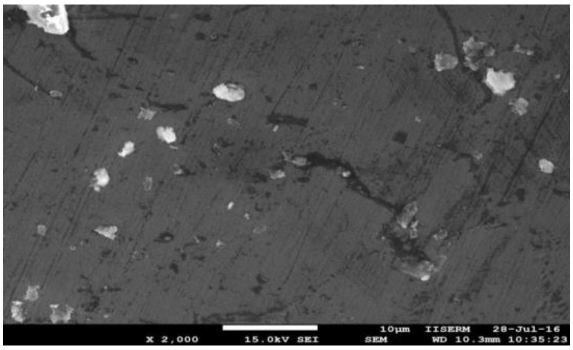


Fig. 3. SEM image of MMC at 12 % reinforcement and 100 mesh size.

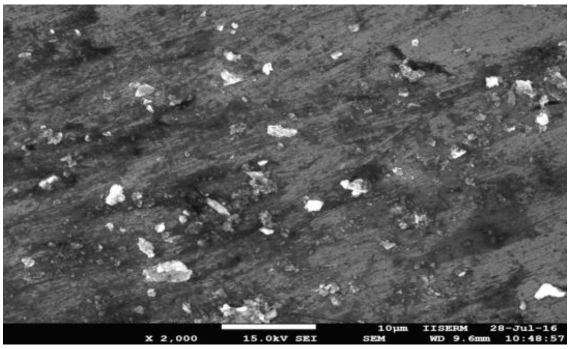


Fig. 4. SEM image of MMC at 16 % reinforcement and 200 mesh size.

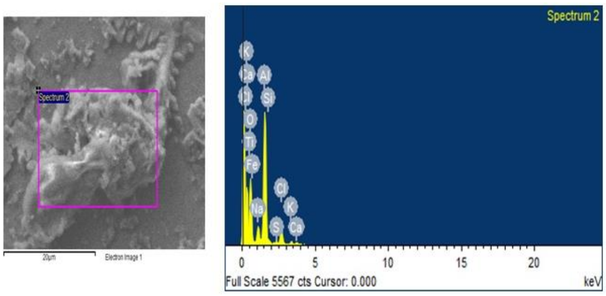


Fig. 5. Energy Dispersive X-Ray Spectroscopy of MMC at 8 % reinforcement and 80 mesh size.

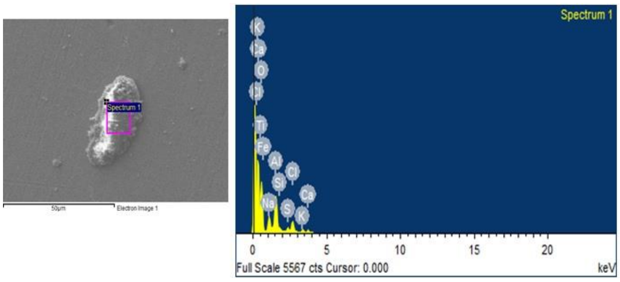


Fig. 6. Energy Dispersive X-Ray Spectroscopy of MMC at 12 % reinforcement and 100 mesh size.

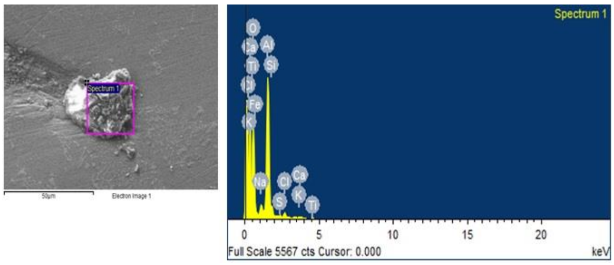


Fig. 7. Energy Dispersive X-Ray Spectroscopy of MMC at 16 % reinforcement and 200 mesh size.

Fig. 8. Optical micrograph of MMC at 8 % reinforcement and 80 mesh size.

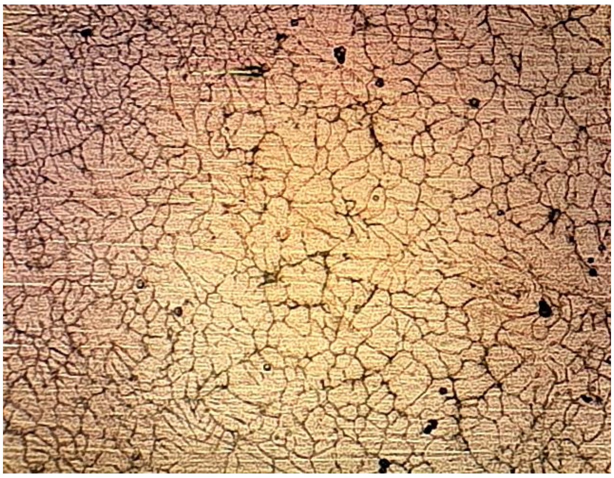


Fig. 9. Optical micrograph of MMC at 12 % reinforcement and 100 mesh size.

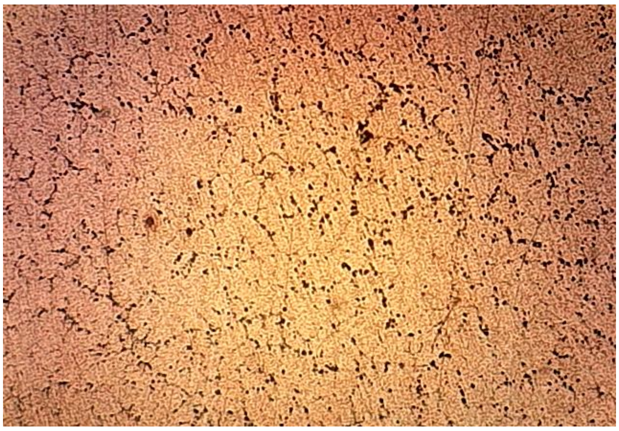


Fig. 10. Optical micrograph of MMC at 16 % reinforcement and 200 mesh size.

Optical micrograph of fabricated composite has been shown in Figs. 8-10. Optical micrograph shows that distribution of reinforcement has been fairly uniform.

4.2 Analysis of control Factor

Investigation of the impact of every control factor (A, B, C, D, E and F) on the specific wear rate was performed with S/N ratio, utilizing a Minitab 17 PC package. Where A represents Temperature in Kelvin, B represents percentage of red mud by weight, C represents particle size in mesh number, D represents applied load in kgf, E represents sliding distance in meters, F represents sliding speed in rpm. Specific wear rate (mm^3/Nm) has been represented as SWR.

Table 2. Experimental layout and results with computed S/N proportions for specific wear rate of MMCs.

Sr. No.	A	B	C	D	E	F	SWR	S/N Ratio
1	1	1	1	1	1	1	0.0000295	90.618
2	1	1	2	2	2	2	0.0000143	96.881
3	1	1	3	3	3	3	0.0000034	109.396
4	1	2	1	1	2	2	0.0000560	85.035
5	1	2	2	2	3	3	0.0000176	95.080
6	1	2	3	3	1	1	0.0008877	61.035
7	1	3	1	2	1	3	0.0006896	63.229
8	1	3	2	3	2	1	0.0006890	63.235
9	1	3	3	1	3	2	0.0000096	100.336
10	2	1	1	3	3	2	0.0000153	96.323
11	2	1	2	1	1	3	0.0001117	79.036
12	2	1	3	2	2	1	0.0000237	92.520
13	2	2	1	2	3	1	0.0000842	81.492
14	2	2	2	3	1	2	0.0009287	60.642
15	2	2	3	1	2	3	0.0000918	80.747
16	2	3	1	3	2	3	0.0009899	60.089
17	2	3	2	1	3	1	0.0000554	85.127
18	2	3	3	2	1	2	0.0004290	67.350

Table 2 demonstrates the experimental plan and their outcomes with S/N ratio for specific wear rate of the composites. The right half of the table incorporated the results of the specific wear rate and the computed S/N ratio values. The reaction table of the specific wear rate is exhibited in Table 2. It demonstrates the S/N ratio at every level of control element and how it was changed at the point when settings of every control variable were changed from one level to another.

The control parameter with the most impact was dictated by difference in values. The higher the difference, the more influential has been the control parameter. The higher the distinction, the more powerful was the control component or communication of two controls. The control parameter and their associations were sorted in connection to the distinction values. It can be seen from the Table 3 that strongest influence on parameter is exerted by sliding distance (factor E), followed by percentage of red mud in the composite (factor B), load on the material (factor D) and by the temperature of the specimen (factor A). Specific wear rate of the composite decreased with increasing sliding distance and percentage of red mud.

Table 3. S/N response table for Specific wear rate of MMCs.

	A	B	C	D	E	F
Level 1	64.97	53.23	65.23	66.79	50.29	58.98
Level 2	58.15	57.34	60.00	62.76	59.75	64.43
Level 3		74.10	59.44	55.12	74.63	61.26
Diff.	6.82	20.87	5.79	11.67	24.33	5.45
Rank	4	2	5	3	1	6

Figures 11 and 12 shows the mean value of means and S/N ratio of wear rate at each level of input parameters. It can be seen that specific wear rate increased with increase in temperature. The more prominent is the S/N ratio; the lower is the fluctuation of specific wear rate around the targeted value. Ideal testing states of these control components could be effortlessly decided from the response diagrams. The diagrams demonstrate the change of the S/N ratio when the setting of the control factor was changed from one level to another. The best specific wear rate value has been at the higher S/N values in the reaction diagrams. It was found that sliding distance and percentage of red mud had the greatest effect on influence the optimal testing condition. The composite with lower particle size prompted higher wear because of simple for expulsion of particle from spot. Some agglomeration of particles in the composites of small size reinforcement would help in loss of more material.

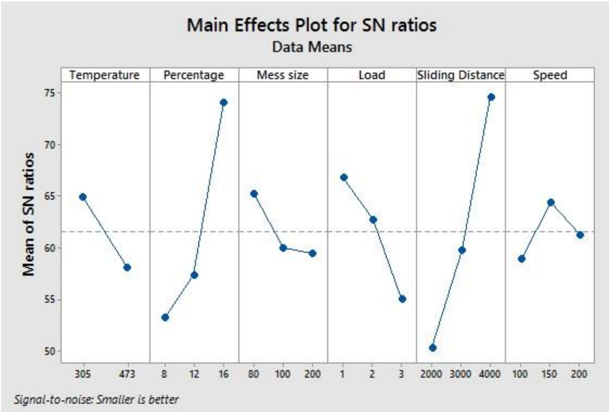


Fig. 11. Main effect plot for S/N ratios.

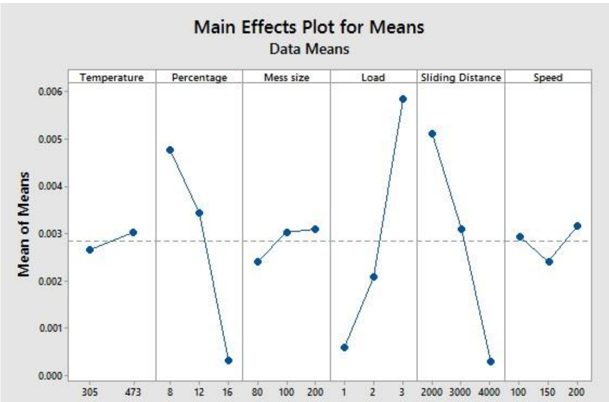


Fig. 12. Main effect plot for Means.

The examination of variance (ANOVA) in Table 4 was utilized to explore which design parameters fundamentally influence the quality characteristic.

Table 4 ANOVA table for specific wear rate.

Source	DOF	Sum of squares	Mean of squares	F value	P value	Contribution
A	1	210.29	210.29	17.38	0.006	5.01 %
B	2	1471.38	735.69	60.82	0.000	35.11 %
C	2	121.82	60.91	5.04	0.052	2.90 %
D	2	423.27	211.64	17.49	0.003	10.10 %
E	2	1802.18	901.09	74.49	0.000	43.01 %
F	2	89.08	44.54	3.68	0.091	2.13 %
Error	6	72.58	12.10			1.73 %
Total	17	4190.60				

As we know different parameter affects the specific wear rate at different degree. From the analysis of variance or ANOVA it can be seen that which design parameter affects the output. It was refined by separating the total variability of the S/N ratio, which is measured by whole of the squared deviations from the total mean S/N ratio, into contributions by each of the design parameters and the errors. Examination of the ascertained estimations of Fishers (F) for all control factors also showed a high impact of parameters E, B, D and A and low impact of parameters C and F on specific wear rate of MMCs. ANOVA shows that the percentage of reinforcement, sliding distance and load has the significant effect on the specific wear rate while speed and mesh size are less significant and speed was found to be least significant. P value of C and F is more than 0.05, so it shows that they are not significant. Since the P value of the factor A, B, D and E were all less than 0.05 and have a significant effect on specific wear rate.

The wear conduct of composites at elevated temperatures has been much intricate than that at room temperature, in light of the fact that temperature impact may affect numerous adjustments in the factors that are included in the wear procedure. It has been shown by the wear test that when the specimen temperature is increased, the wear resistance of all the composites decreased. This may be due to softening of the composite materials at high temperatures, resulting in loss of the strengths. Moreover, at high temperature oxidation can be another reason for increase in wear, in light of the fact that at room temperature the possibility of wear oxidation to happen is just at the contact surfaces where friction heat was produced because of rubbing of wearing surfaces. In high temperature wear the entire sample was heated, which brought about oxidation of the specimen surface; under mechanical attack in the wear procedure the oxides were separated. In this way loss of the material is increased. The contribution of residual error is less than 2 % which means it can be neglected.

4.3 Confirmation test

Table 5 demonstrates the testing conditions used to get the specific wear rate of MMCs for affirmation tests. Once the ideal level of the configuration parameters has been chosen, the last step was to anticipate and confirm the development of the quality characteristics taking into account optimum level of design parameters. The built up S/N ratio (μ_i) utilizing the optimum level of the configuration parameters could be computed as:

$$\mu_i = \sum_{i=0}^{p} (\mu_i - \mu_m) + \mu_m \quad (4)$$

where, μ_m denotes the total mean of the S/N ratio, μ_i denotes the mean S/N ratio at optimal level and p is the number of parameter that affects the response.

Table 5. Confirmation test table.

Optimum levels	$\mu_{i, cal}$	SWR_{cal}	$\mu_{i, exp}$	SWR_{exp}	($\mu_{i, cal}$ - $\mu_{i, exp}$)
$A_1B_1C_3D_1E_3F_2$	122.235	0.776	119.743	1.03	2.582

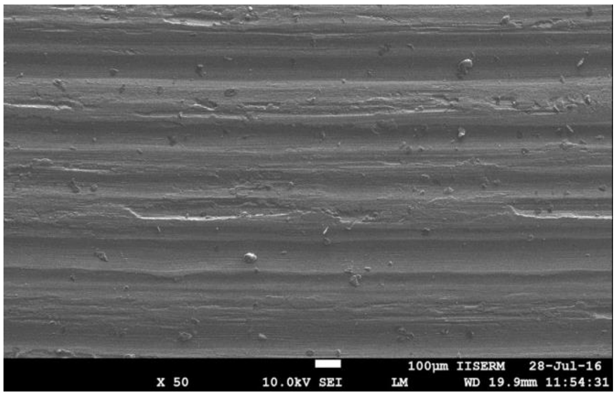
The optimum level for experiment is $A_1B_1C_3D_1E_3F_2$. Since in Taguchi Table 2 there is no experiment which matches with the optimum level, so experiment have to be performed keeping these optimum levels. Table 5 above shows the S/N ratio value for calculated ($\mu_{i,\ cal}$) and experimental ($\mu_{i,\ exp}$) setup. Table 5 draws out the comparison between theoretical and experimental value at optimal testing conditions. From the calculations of ANOVA and Taguchi analysis optimal testing parameters came out to be level 1 of the temperature (A_1), level 1 of the percentage of the reinforcement (B_1), level 3 of the size of reinforcement (C_3), level 1 of the load (D_1), level 3 of the sliding distance (E_3) and level 2 of the sliding speed (F_2). The specific wear rate at the optimal condition is calculated by the use of equation 2. The theoretical value of specific wear rate (SWR_{cal}) came out to be ($0.776*10^{-6}$) at optimal conditions by using equation 2. The experimental value of specific wear rate (SWR_{exp}) came out to be ($1.03*10^{-6}$).

It can be seen there is a reasonable difference between S/N values of theoretical and experimental value. The mathematical model given in equation five can be effectively used to predict the specific wear rate of the fabricated composite.

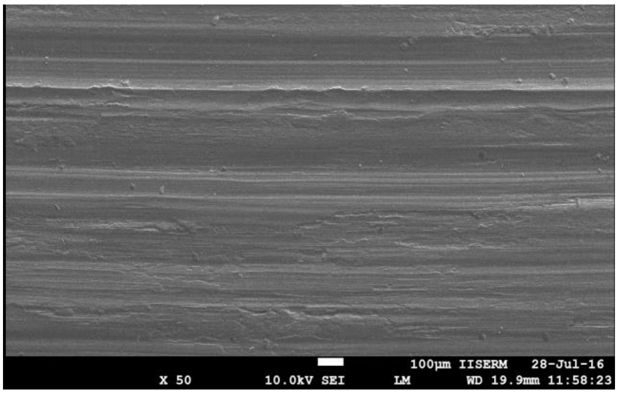
$$SWR=-0.000212+0.000037\ A+0.000222\ B \\ 0.000035\ C+0.000263\ D-0.000241\ E+0.000011 \quad (5)$$

4.4 Morphological analysis

The analysis of worn surface at room and elevated temperature by SEM is shown in Fig. 13 (a, b). An investigation of the morphologies of the worn surface show the presence of abrasion and delimination wear in these composites. Examination of Fig. 13 shows that high form of abrasion wear was predominant at room temperature while examination of Fig. 13 shows the wear is more of delimination type.



a)



b)

Fig. 13. Scanning electron micrograph of worn surface (a) at Room Temperature and (b) at elevated Temperature.

The presence of smooth lines in direction of sliding wear is very apparent at high temperature indicates that there might be softening of composite at high temperature. Since at room temperature the composite is hard as compared that at high temperature so the cracks and cavities observed were more visible than at high temperature.

5. CONCLUSIONS

The following conclusions can be drawn from the specific wear rate of the following aluminium composite reinforced with red mud.

1. The results show that, the higher effect on specific wear rate of the composite is of

sliding distance and percentage of reinforcement i.e. red mud in the composite while size of reinforcement and sliding speed have lesser effect on specific wear rate.

2. The results show that specific wear rate of the composite increased at elevated temperature. The reason for increased wear rate at high temperature is may be due to loss of wear resistance at high temperature by softening of matrix.
3. With the change in temperature of the specimen the wear behaviour changed from abrasive to delimination. At room temperature wear due to abrasion is more prominent while at high temperature wear due to delimination is more prominent.
4. Confirmation test showed that S/N values can be calculated for optimal testing conditions. Predicted and actual value of specific wear rate showed good reasonable agreement and can be used to predict specific wear rate.

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