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Full Length Article

Dry sliding wear behavior of epoxy fly ash composite with Taguchi optimization

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ABSTRACT

Epoxy resin matrix composite reinforced with fly ash particles was prepared by ultrasonic stirring method. Pin-on-disc wear test of the composite was carried out and compared according to Taguchi design-of-experiment. An orthogonal array exhibited and examined the influencing parameters like % of fly ash debris, typical load, sliding speed and track distance on the composite. Signal to noise ratio analysis optimizes the parametric condition that yields minimum wear rate, minimum frictional force and minimum coefficient of friction. A multi-criteria decision analysis method, TOPSIS is used to optimize the output, and confirmation test has been done to verify the projected model. ANOVA shows that applied normal load plays a vital role in increasing dry sliding wear of epoxy composites.

1. Introduction

Polymer matrix composites are advanced materials that have high strength at low weight, which make them usable at various applications like automobile, aerospace and household appliances. The decision of material for a specific application relies on the variables like material expense, thickness, quality and working conditions. Polymer composites which are used in sliding conditions are normally employed in low energy transfer. The possible reason in sudden increase in wear rate is due to the frictional temperature reaching the material melting temperature under the loading condition [1]. Hence, wear is one of the real issues that should be handled to enhance the life of the part [2]. This will bring higher working temperature with increment in wear and leads to speedier substitution of parts [3]. Lightweight polymer matrix composites are the most suitable materials for weight sensitive application in aerospace and automobile industries. Current work concentrates on waste utilization, product development as a composite material which result better wear properties. Deuis et al. (1996) [3] explained the impact of volume percentage, sliding conditions (time, distance, speed, etc.) and applied load that impacts the dry sliding wear of the composites.

Biswas and Satapathy (2010) [4] concluded that the particulate filled polymer composites are mostly encouraging building materials because of their reasonable determination of lattice and fortifying strong molecule stage. It prompts a composite with a blend of quality modulus better than those of traditional metallic materials. Polymer composites have replaced the traditional metal and ceramic materials in making high strength and low conductivity applications like pump wear ring, bushings, line shaft bearings, interstage bushings and pressure reducing bushings. Laguna-Camacho et al., (2015) [5] suggested that unreinforced epoxy were not satisfactory because of its high fragility. The consideration of ceramic fillers into polymers for commercial application rises, and it enables good aesthetic sense with good mechanical properties. Silica assumes an imperative part in enhancing electrical, mechanical and thermal properties of the material. Fly ash is an industrial waste, largely available in thermal power plants, which mostly contains silica and alumina. Fly ash has been used earlier as a reinforcing material in polymeric materials, but a few investigations have been carried out on tribological properties of the material by varying different parameters of pin on disc sliding wear. Xu et al. (2015) [6] described that the sliding is mainly influenced by contacting parts and tribological behavior of the materials. To make a suitable wear resistant composite, one has to evaluate the relation between varying parameters and wear rate. This technique has effectively sought parametric evaluation in different wear procedures of an extensive variety of polymer composites [7–10].

In our investigation, tribological behavior of the fly ash reinforced epoxy polymer composite is measured, and wear, frictional

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force and coefficient of frictional are tabulated. Optimization technique is applied to get the suitable combination to get the minimum value of wear. The percentage contribution of each parameter is evaluated.

2. Experimental details

2.1. Matrix and filler materials

Epoxy resin (LY 556), a high viscous semi-solid material having density 1120 gm/cm^3 is utilized as the matrix material whose chemical name is Bisphenol-A-Diglycidyl-ether. An amino group hardener (HY 951) is used for hardening the material. Both the epoxy resin and the hardener are supplied by ATUL Industries Pvt. Ltd, Kolkata. Epoxy acts as a good matrix material due to its high corrosion resistance, high thermal stability and good mechanical properties. Fly ash being a ceramic filler is used as a reinforcement. Fly ash (Class C) used in this experimental work is collected from CPP 2 of Rourkela Steel Plant, Odisha. The fly ash particles are spherical in shape as revealed by the SEM micrographs as shown in Fig. 1. A graph has been plotted between particle size and volume percentage of fly ash from the data provided by the particle size analyzer (MALVERN MASTERIZER). The average particle size is 27.26 μm as determined from the Fig. 2. Normally, if the particle size is in the order of nanometer then it reduces the friction and wear [11]. But here, the particle size is in the order of micrometer which increases the rate of wear. The detail chemical compositional analysis shown in Table 1revealed that the major elements present in fly ash are 46% SiO_2 and 35% Al_2O_3 which makes it a good ceramic material. Si and Al make the fly ash harder, rigid and give more flexibility as a filler material.

2.2. Composite fabrication

Epoxy resin and fly ash are mixed in four different weight percentages and put under an ultrasonic sonicator with its horn dipped partially inside the mixer for 10 min with a pulse time of 5 sec. Once it is complete, 10 wt % of hardener is added and hand stirred gently to avoid trapping of bubbles, and poured into plastic pipes of 10 mm diameter and 1 inch in height, and allowed to cure at room temperature for 24 hrs. Once it is hardened, the plastic pipes were cut to remove the solidified cylindrical samples which are dimensionally accurate for the pin-on-disc (DUCOM) machine. Briscoe (1990) [12] explained that temperature, pressure, strain rate and even the environment may make an enormous difference to the mechanical response of polymers. So, controlled atmosphere is maintained while making of samples for uniformity.

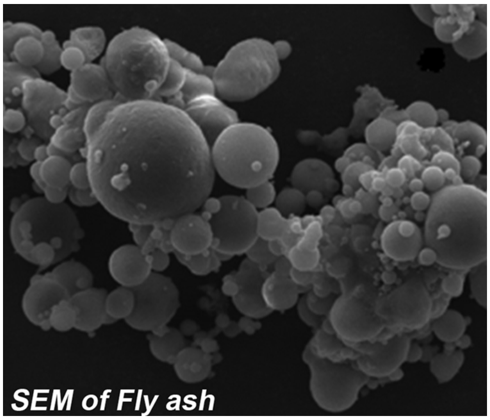

Fig. 1. SEM micrograph of fly ash particles.

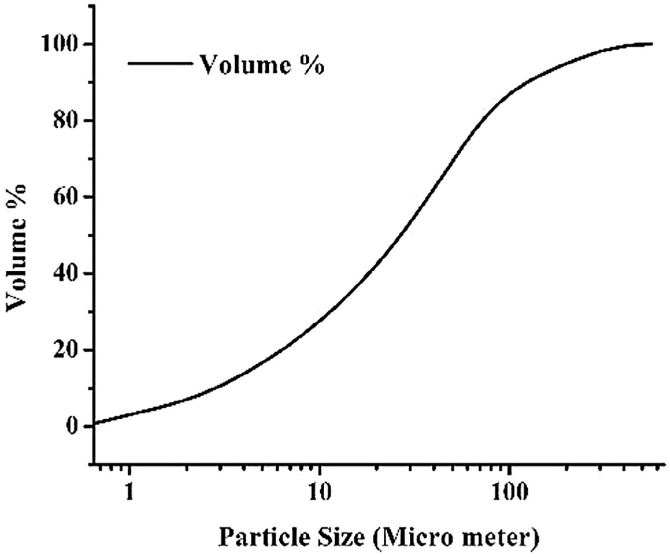

Fig. 2. Particle size analysis of fly ash particles.

2.3. Dry sliding wear test

Dry sliding wear test has been carried out in pin-on-disc machine as per ASTM G99 standard. This ASTM standard is fixed for polymeric samples. The disc of the machine is made up of stainless steel with negligible amount of surface roughness. The specimen is held tight with the help of a sample holder and screws and perpendicular to the rotating disc with four screw fasteners, and load is applied with a lever attachment. Other parameters, like time of rotation, speed in RPM and track diameter have to be fixed manually prior to each experiment. Fig. 3shows a schematic diagram of sliding wear machine with different attachments. Here, the load has to be provided manually by placing discs of desired weight prior to each experiment. An AC motor helps in rotating the disc, while the flat sample surface remains fixed and unmoved.

Virtually, all of the frictional work ultimately appears as heat which is conducted out of the boundaries of the system. However, there will be volumes of material adjacent to the contacts where the work is initially dissipated mainly in inelastic deformations. These regions will be called the primary energy dissipation zones [13]. It is noted that the wear increases with increase in normal applied load and sliding distance [14].

2.4. Experimental design

Kumar and Dhiman (2013) [15] described how wear is a critical parameter while considering the characterization of any material.

Table 1
Chemical compositional analysis of fly ash.

Constituents	Vol %
Fe_2O_3	8.1
MgO	1.14
Al_2O_3	24.98
SiO_2	55.85
P_2O_5	0.15
SO_3	1.16
K_2O	0.85
CaO	2.54
Na_2O	0.2
TiO_2	1.75
CO_2	1.56

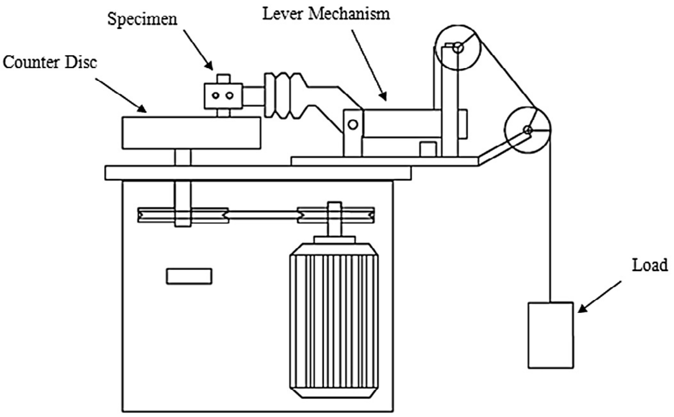

Fig. 3. Schematic diagram of pin-on-disc machine.

Quality and wear properties are the dominating issues confronted by industries regarding the production of epoxy resin matrix composites reinforced with fly ash particles. Henceforth, choice of filler materials which have a huge impact on the strength as well as wear properties of the composite is very important as it very much affects the quality life of the component.

The objective of this study is to conduct tests utilizing Taguchi's design of experiments methodology to figure out the ideal levels of parameters that will yield maximum dry sliding wear resistance. In this tribological experiment work, percentage of reinforcement of fly ash, duration of sliding, speed, track diameter and load were considered as five control variables and altered at different levels as demonstrated in Table 2. To find out the influence of parameters on the desired output, Taguchi based orthogonal array has been taken, which has the capacity to assess two or more parameters concurrently and individually that will influence the variability of a specific process characteristic using utilizing least number of tests. Considering these control factors, L32 orthogonal cluster was found to be suitable. Additionally, in the present work, no noise parameters are considered. L32 orthogonal array indicated in Table 3contains outcomes of 32 different combinations of factors. The signal to noise ratio is obtained from the experimental results obtained. The S/N ratio is of different types. In this experiment, the goal is to minimize the wear and thus, it is Lower-the-Better type characteristic. Despite the performance characteristics, a noteworthy signal to noise ratio resembles to better performance with least variation. The S/N ratio is calculated as follows-

$$\eta = -10\log_{10}\left[1/n\sum y_i^2\right] \quad \text{where} \quad 1 \le i \le n \tag{1}$$
$$n = \text{no of experiments carried out}$$

Therefore, the ideal level of the input factors is the combination of individual parameters with levels having the maximum signal to noise ratio.

Table 2
Levels of variables used in the experiment.

Control Factors	Unit	Levels			
		1	2	3	4
Time (A)	min	5	10		
% of FA (B)		10	20	30	40
Speed (C)	RPM	200	400	600	800
Track Diameter (D)	mm	40	50	60	70
Load (E)	N	10	20	30	40

Table 3
Thirty-two orthogonal array with results.

Sl no	% FA	Time (Min)	Speed (RPM)	Load (N)	Track diameter (cm)	Wear	Frictional force (N)	COF (μ)	Relative closeness coefficient (P)
1	10	5	200	10	40	140	2.77	0.04	0.82856
2	10	5	400	20	50	250.78	10.17	0.04	0.615883
3	10	5	600	30	60	147.09	14.79	0.05	0.643091
4	10	5	800	40	70	371.35	22.18	0.05	0.260846
5	10	10	200	40	40	136.15	20.17	0.04	0.562478
6	10	10	400	30	50	171.58	11.2	0.05	0.684963
7	10	10	600	20	60	333.52	6.34	0.05	0.566212
8	10	10	800	10	70	60.08	9.98	0.04	0.826147
9	20	5	200	10	50	134.27	3.83	0.05	0.822666
10	20	5	400	20	40	47.91	11.43	0.05	0.788616
11	20	5	600	30	70	297.03	17.13	0.05	0.434593
12	20	5	800	40	60	272.15	23.03	0.06	0.362369
13	20	10	200	40	50	505.83	27.39	0.06	3.80E-06
14	20	10	400	30	40	145.41	14.01	0.05	0.65989
15	20	10	600	20	70	395.76	9.98	0.05	0.458599
16	20	10	800	10	60	108.99	2.05	0.05	0.853708
17	30	5	200	20	60	60.98	7.93	0.04	0.873544
18	30	5	400	10	70	21.87	3.84	0.04	0.999999
19	30	5	600	40	40	197	16.92	0.05	0.552097
20	30	5	800	30	50	91.48	13.36	0.05	0.720155
21	30	10	200	30	60	222.23	12.77	0.04	0.607281
22	30	10	400	40	70	248.9	19.45	0.05	0.450608
23	30	10	600	10	40	281.17	3.31	0.05	0.648674
24	30	10	800	20	50	408.76	7.48	0.05	0.484069
25	40	5	200	20	70	110.65	5.13	0.05	0.845886
26	40	5	400	10	60	54.78	2.21	0.05	0.909899
27	40	5	600	40	50	297.21	13.22	0.05	0.504077
28	40	5	800	30	40	46.83	9.71	0.05	0.827162
29	40	10	200	30	70	144.34	8.81	0.05	0.757246
30	40	10	400	40	60	120.27	11.85	0.05	0.726858
31	40	10	600	10	50	31.02	3.31	0.05	0.931367
32	40	10	800	20	40	43.88	9.85	0.05	0.825404

2.5. Basics of TOPSIS method

The traditional TOPSIS strategy is taking into account the thought that the best option ought to have the most limited separation from the positive perfect arrangement and the best separation from the negative perfect arrangement. TOPSIS model shows the alternative ways of normalizing the data and measuring the distances from the mean position. TOPSIS method has superior advantages with regard to the adaptability of its evaluation method and the accuracy of evaluation result. The TOPSIS method consists of the following steps:

a. Normalizing the decision matrix

$$r_{ij} = \frac{X_{ij}}{\sqrt{\sum_{k=1}^{m} X^{2}_{kj}}}, i = 1,\ldots m;\ j = 1,\ldots n \tag{2}$$

Multiplying the columns of normalized matrix with associated weights. Here, similar weights have been assigned to each parameter, i.e.0.33.

$$Vij = W_j \times r_{ij}, \tag{3}$$

b. Determine the positive ideal and negative ideal solutions respectively,

$$A^{+} = \left\{v_1^{+}, v_2^{+}, \ldots v_n^{+}\right\} = \left\{\left(\max v_{ij} \middle| j \in K_b\right)\left(\min v_{ij} \middle| j \in K_c\right)\right\} \tag{4}$$

$$A^{-} = \left\{v_1^{-}, v_2^{-}, \ldots v_n^{-}\right\} = \left\{\left(\min v_{ij} \middle| j \in K_b\right)\left(\max v_{ij} \middle| j \in K_c\right)\right\} \tag{5}$$

Where, K_b = Set of benefit criteria
K_c = Set of cost criteria
Obtaining the distances of the existing alternatives from the positive ideal and negative ideal solutions, two distances for each alternatives are, respectively, calculated as follows:

$$S_i^{+} = \sqrt{\sum_{j=1}^{n}\left(v_{ij} - v_j^{+}\right)}^{2}, i = 1, 2 \ldots m \tag{6}$$

$$S_i^{-} = \sqrt{\sum_{j=1}^{n}\left(v_{ij} - v_j^{-}\right)}^{2}, i = 1, 2 \ldots m \tag{7}$$

c. Calculate the relative closeness to the ideal alternatives;

$$RC_i = \frac{S_i^{-}}{S_i^{+} + S_i^{-}} \quad i = 1, 2 \ldots . m \quad 0 \le RC_i \le 1 \tag{8}$$

d. Rank the alternatives according to their relative closeness to the ideal alternatives, the bigger RC_i, the better alternative A_i.

2.6. Microstructure

Microscopic observations have been carried out to have a better perspective of worn out surfaces arising from different variable combinations bearing reinforcement in the epoxy resin matrix. Samples subjected to wear test are examined in a JEOL 6480LV scanning electron microscope. Samples were magnified at 100× and 200× with an accelerating voltage of 15 kv to show the wear tracks and deformation formed due to sliding wear [16].

3. Results and discussion

3.1. Statistical analysis

In this study, thirty-two no. of experiments have been done to analyze the impact of different parameters on the wear, frictional force and coefficient of friction. These trials are led according to the L32 orthogonal array exhibit, and results are demonstrated in Table 3. As it is a multi-objective optimization problem, the major objective is to make it a single objective problem. By applying TOPSIS method, the three output responses are converted into a single response optimization situation with the objective function is overall relative closeness value. The optimal parametric combination is then assessed which would come about most noteworthy relative closeness value. The optimal factor setting for maximizing this single response can be performed by Taguchi strategy. The average wear values for diverse levels of selected parameters are indicated in Table 4. From here, it is understood that, when time is at level 1(5 min), the average wear rate values are higher than the wear rate obtained at time level 2 (10 min). So among these three levels of time, level 1 is the best. This is to be expected since as the time increases, the wear rate of the composite decreases. On comparable lines, level 4 (40%) for FA, level 2 (400 RPM) for speed, level 1 (10 N) for load and level 1 (40 cm) for track diameter are selected. Fig. 4shows the main effects plot for S/N ratio obtained from the software having unit in dB, which substantiates the conclusions drawn from Table 4.

Table 4
Mean response table for relative closeness coefficient.

Level	Time	% FA	Speed	Load	Track diameter
1	−3.764	−4.529	−15.742	−1.445	−3.067
2	−10.229	−17.476	−2.961	−3.573	−16.644
3		−3.813	−4.784	−3.652	−3.508
4		−2.168	−4.499	−19.316	−4.767
Delta	6.465	15.308	12.782	17.871	13.576
Rank	5	2	4	1	3

Delta = maximum value–minimum value.

The hugeness of the variables on reactions has additionally been uncovered quantitatively by examination of difference strategy (ANOVA). It is a measurable system, which can interpret some vital conclusions taking into record examination of the test information. The procedure is to a great degree accommodating to reveal the level of essentiality of effect of factor(s) on a specific reaction. It secludes the total variability of the reaction (total of squared deviations about the terrific mean) into commitments rendered by each of the parameter and the blunder [17]. ANOVA for relative closeness coefficient has been indicated in Table 5(all notations convey their typical implications). Depending on P-value, the relative importance of the factor effect on relative closeness coefficient can be spotted. Table 5 also uncovers the factors which has no direct impact on significance of relative closeness coefficient, but the relative significance is highest for load and % FA, and at the same time it is lowest for time. In Table 5, the P value denotes the percentage contribution of each parameter. As the P value decreases, the contribution increases. When the P value is less than 0.5, it implies that the parameter is more significant in determine the wear characteristics of the material.

3.2. Confirmatory experiment for minimum wear rate

The confirmatory experiment concludes that the optimal setting parameters derived previously will actually yield an improvement in quality characteristic and how close are the respective predictions with the real ones. In the wake of assessing the optimal parameter settings, the following step is to anticipate and check the enhancement of quality characteristics utilizing the optimal parametric combination. The estimated relative closeness coefficient

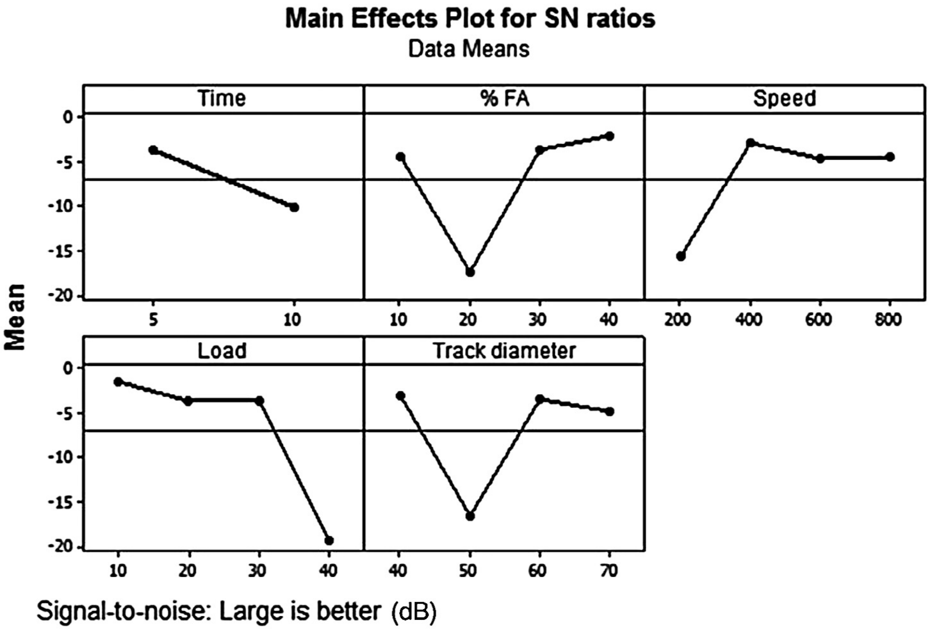

Fig. 4. S/N ratio plot for relative closeness coefficient.

$\hat{\gamma}$ using the optimal level of the design parameters can be calculated as:

$$\hat{\gamma} = \gamma_m + \sum_{i=1}^{n}(\bar{\gamma} - \gamma_m) \tag{9}$$

Where γ_m the total is mean grey relational grade, $\bar{\gamma}$ is the mean grey relational grade at the optimal level, and n is the number of the main design parameters that affect the quality characteristics. Table 6represents the comparison of the predicted values of input parameters with that of actual by using the optimal conditions. The error is calculated to determine the variation of actual result from the predicted value. A good agreement between the two has been observed with a difference of 0.93 shows that there is least variation in predicted and actual value.

Table 5
ANOVA table with adjusted sum of square for tests.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Time	1	0.018507	0.018507	0.018507	2.65	0.121
% FA	3	0.262953	0.262953	0.087651	12.57	0.000
Speed	3	0.093677	0.093677	0.031226	4.48	0.016
Load	3	0.785823	0.785823	0.261941	37.56	0.000
Track diameter	3	0.078732	0.078732	0.026244	3.76	0.029
Error	18	0.125542	0.125542	0.006975		
Total	31	1.365234				

3.3. *Morphology of wear surfaces*

The SEM analysis of wear surfaces 20% FA reinforcement with 20 N and 40 N of applied load is shown in the Fig. 5, as it is showing the good wear tracks and plastic deformation of material. It reveals that particulate reinforcement plays an important role in increase of wear rate. The white patches shows the plastic flow of the material, and it is due to the frictional heat generated at the sliding surface. Fig. 5(b) and (c) show smoother surfaces at lower normal loading condition. In these figures, we can find difference in height of wear track which may be due to direct contact of reinforcement material with the disc. Fig. 5(a) and (d), which is at higher normal load, shows some distortion and more plastic flow of material. The plastic flow and overlapping of material is shown in circle marks. The straight lines shows the directional path of wear. It may be due to the heat generated by the friction generated at the interface. It may be due to release of filler fly ash particles at high temperature and friction which ultimately results in layer formation of only matrix material, i.e. epoxy resin. As plastic flow of matrix material starts, the embedded round shaped

Table 6
Confirmatory test results.

	Initial parameter setting	Optimal parameter condition	
		Predicted value	Experimented value
Level of factors	A2B3C1E3D2	A1B4C2D1E1	A1B4C2D1E1
Time	10		5
% FA	30		40
Speed	200		400
Load	30		10
Track diameter	50		40
Relative coefficient value	0.9999		
S/N ratio (dB) of relative coefficient value		14.5811	14.4461

Improvement in relative coefficient value = 0.93%.

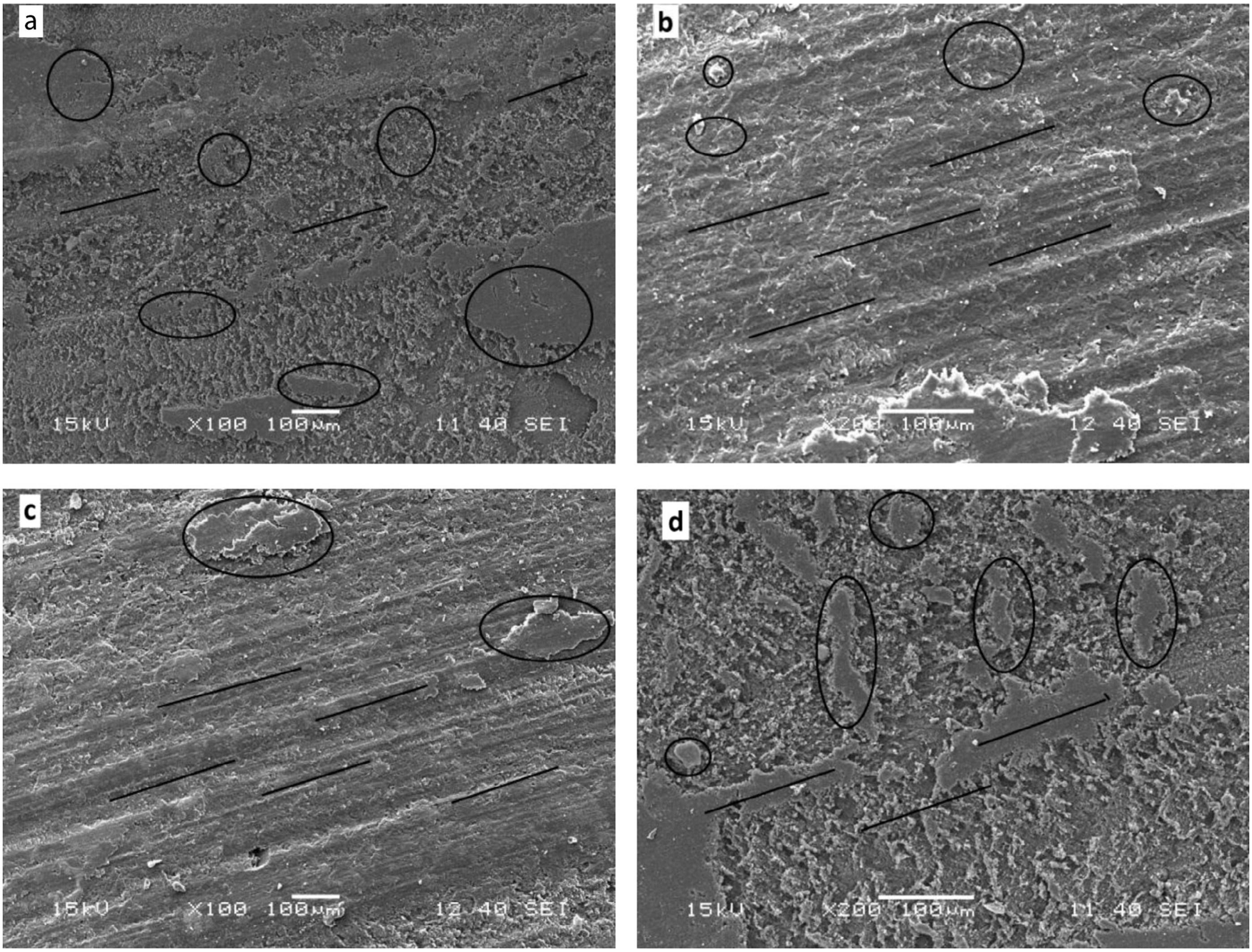

Fig. 5. SEM micrographs of wear surfaces.

fly ash particles come out and help in formation of craters and wear tracks.

4. Conclusions

In tribology, frictional work is done and some of this work is dissipated within the polymeric matrix and the ceramic reinforcement. Virtually, all of the frictional work appears as wear loss and heat generated in the system. However, there will be volumes of material adjacent to the contacts where the work is initially dissipated mainly in inelastic deformation. The experimental design and analysis of the fly ash epoxy resin composite gives the following conclusions:

a. Fly fiery debris is a dangerous modern waste which can be utilized as a filler material and can be utilized for business applications.
b. TOPSIS method can be utilized for making the multi objective optimization into a single objective optimization, and Taguchi orthogonal array can be utilized for reducing the number of experiments and getting the optimized result.
c. The significant and influencing parameters are found from ANOVA table. Applied normal load is found to have most influence on the increase in wear, frictional force and coefficient of friction followed by % reinforcement, track diameter, speed and time.
d. As the percentage of error is minimal, we can conclude that Taguchi orthogonal array has given the most accurate result with least possible number of experiments.
e. The SEM micrographs show formation of circular tracks in the specimen, and it is clearly visible that the fly ash particles erode out when it come in contact with the rotating plate.
f. There may be chances of secondary wear due to the eroded particles from the surfaces which get entrapped in between plate and the sample.
g. There is agglomeration of eroded matrix material due to the heat generated at the sliding surface.
h. In the future, Taguchi optimization method can be utilized in determining the impact of parameters in some other types of wear testing method, or same methodology can be used for other polymer composites.

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