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Short Communication

Sliding wear behavior of E-glass-epoxy/MWCNT composites: An experimental assessment

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A R T I C L E I N F O

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This investigation has evaluated the sliding wear properties of E-glass-epoxy/MWCNT (multiwalled carbon nanotube) composite and Epoxy/MWCNT composite. Four different reinforcements (0, 0.5,1 and 1.5 wt %) of MWCNTs are dispersed into an epoxy resin. Design of experiments (DOE) and Analysis of variance (ANOVA) are employed to understand the relationship between control factors (Percentage of reinforcement, Sliding distance, Sliding velocity and Normal load) and response measures (specific wear rate and friction coefficient). The control variables such as sliding distance (300, 600, 900 and 1200 m) and normal loads of 10, 15, 20 and 25 N and at sliding velocities of 1, 2, 3 and 4 m/s are chosen for this study. It is observed that that the specific wear rate and friction coefficient can be reduced by the addition of MWCNTs. Scanning electron microscopy (SEM) is used to observe the worn surfaces of the samples. Compared with neat epoxy, the composites with MWCNTs showed a lower mass loss, friction coefficient and wear rate and these parameters decreased with the increase of MWCNT percentage. Microscopic investigation of worn out sample fracture surface has revealed that fiber debonding happens when the stresses at the fiber matrix interface exceeds the interfacial strength, causing the fiber to debond from the matrix. The optimum control variables have been derived to reduce both wear and friction coefficient of composites.

1. Introduction

Polymers [1–5] particularly E-glass epoxy based composites are considered as potential candidate materials for various tribological applications [2–4] due to their superior physical and mechanical properties such as high compressive strength, elastic modulus and low density. The remarkable mechanical properties of the carbon nanotubes (CNTs) have inspired the researchers to produce composites by combined CNTs with matrix. Recently, some researchers [1–5] have reported regarding the wear performance of E-glass/epoxy composites. Very little work has been done by researchers to describe the sliding wear of CNT based composites. Wang et al. [6] studied the mechanical and tribological behavior of the blend of PA66/UHMWPE with compatibilizer. The results showed that the addition of UHMWPE reduced the wear rate. Friedrich and Pipes [7] studied the abrasive wear behavior of epoxy reinforced with carbon, glass and aramid fabrics. Harsha and Tewari [8] reported the two-body and three-body abrasive wear behavior of polyaryletherketone composites.

The available literature has not focused on the influence of sliding distance and normal load on tribological characteristics of MWCNTs-E glass/epoxy composites. Tribological properties of such materials in reciprocating contacts depend certainly on the properties of both matrix and reinforcement elements and their interface. It is generally known that the epoxy resins with appropriate curing agents find use as products in protective coatings, adhesives, structural components etc. because of their good mechanical properties, excellent chemical resistance and electrical characteristics. When these epoxy resins are reinforced with high strength glass fibers and carbon nano tubes the resulting product find structural applications in view of light weight and high stiffness. Research is thus needed to understand the degradation of the surface and subsurface of such materials. The objective of the present study is to carry out wear tests on pin-on-disc machine under different various conditions. The main aim of this work is to assess the influence of MWCNT reinforcement on sliding wear behavior of E-glass-epoxy/MWCNT composite.

2. Experimental details

2.1. Materials and methods

The matrix used in this study is an epoxy polymer based on bisphenol-A resin (ARALDITE LY 556, CIBA GEIGY), hardener

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(ARALDITE HY- 5200 – CIBA GEIGY), Rubber (ETBN) and MWCNTs. The diameters of tubes are 20–30 nm and they have a length of 4 microns. Resin (LY556) was taken into a ball milling jar and to this ETBN (separately heated at 40 °C for 15 minutes) was added. To this mixture, MWCNTs were added in a ball milling machine for proper dispersion. Bi-directional E-glass fibers are reinforced separately in epoxy resin to prepare the fiber reinforced composites. The fabrication of the composite slabs is done by conventional hand-layup technique followed by light compression molding technique. The fibers are mixed thoroughly in the epoxy resin. The bidirectional E-glass fiber and the epoxy resin possess Young's modulus of 72.5 GPa and 3.42 GPa respectively and a density of 2600 kg/m^3 and 1200 kg/m^3 respectively. Each ply of fiber is of the dimension 200 × 200 mm^2. E-glass/epoxy–MWCNTs composites were manufactured by the compression molding process. The panels were cured for about 12–15 h at room temperature and then thermally post cured at 110 °C for 3 h. The fiber volume fraction for the E-glass/epoxy–MWCNTs composites fabricated by this process was found to be around 54% and void content of 3%.

2.2. *Test apparatus*

A pin-on-disk test setup (ASTM: G99) was employed to investigate the wear behavior of E-glass-epoxy/MWCNT composite (90° bidirectional). The disc used was an alloy steel with 165 mm diameter and 8 mm thickness, hardness of 62 HRC. The specimen of size (10 mm diameter) was positioned within the specimen holder normal to the steel disk. Before conducting the test, the disk was cleaned with acetone. The alumina paper was placed on a rotating disc with an adhesive. Three trials were conducted for each specimen individually in the pin-on-disk test rig and the average values were used. Tests were performed as per the chosen variables given in Table 1. The weight of the specimen is measured using an electronic balance. The initial and final weights of specimen were recorded to determine the weight loss. The specific wear rate was estimated as the ratio of wear loss and product of normal load and sliding distance. Friction coefficient was directly taken from the apparatus.

2.3. *Taguchi method: design of experiments*

Based on the preliminary investigations, the input parameters chosen were: Percentage of reinforcement, Sliding distance (m), Sliding velocity (m/s) and Normal load (N). The working range of input parameters and the levels taken is shown in Table 1. Two major tools used in this method are (i) S/N ratio to measure the quality and (ii) orthogonal arrays to accommodate many factors affecting simultaneously to evaluate the tribological performances. As per the Taguchi quality design concept [6–16], an L16 orthogonal array table with 16 rows was chosen for the experiments (Tables 2 and 3). In the present study all the designs, plots and analyses have been carried out using Minitab statistical software. There are several S/N ratios available depending on the type of characteristics. The characteristic where lower value represents better performance, such as wear rate, is called 'lower is better,' LB [6]. Statistical study has been performed to evaluate the effect of reinforcement and other variables on specific wear rate and friction coefficient of E-glass/epoxy composite. The objective of analysis of variance (ANOVA) is

Table 1
Input process parameters and their levels.

Parameters	Level 1	Level 2	Level 3	Level 4	Units
Percentage of reinforcement (A)	0	0.5	1	1.5	mm^3/N-m
Normal load (B)	10	15	20	25	N
Sliding velocity (C)	1	2	3	4	m/s
Sliding distance (D)	300	600	900	1200	m

Table 2
Experimental design using L16 orthogonal array (Epoxy/MWCNT).

Expt. no.	Percent of reinforcement (A)	Normal load (B)	Sliding velocity (C)	Sliding distance (D)	Specific wear rate × 10^{-4}	Coeff. of friction
1	0.0	10	1	300	5.0	0.50
2	0.0	15	2	600	5.5	0.52
3	0.0	20	3	900	6.0	0.54
4	0.0	25	4	1200	6.5	0.60
5	0.5	10	2	900	4.6	0.42
6	0.5	15	1	1200	5.0	0.50
7	0.5	20	4	300	4.1	0.42
8	0.5	25	3	600	4.0	0.41
9	1.0	10	3	1200	3.6	0.43
10	1.0	15	4	900	3.1	0.39
11	1.0	20	1	600	2.9	0.34
12	1.0	25	2	300	4.0	0.31
13	1.5	10	4	600	2.4	0.21
14	1.5	15	3	300	2.6	0.23
15	1.5	20	2	1200	3.5	0.25
16	1.5	25	1	900	3.1	0.24

Table 3
Experimental design using L16 orthogonal array (E-glass-epoxy/MWCNT).

Expt. no.	Percent of reinforcement	Normal load	Sliding velocity	Sliding distance	Specific wear rate × 10^{-6}	Coeff. of friction
1	0.0	10	1	300	4.1	0.40
2	0.0	15	2	600	4.6	0.46
3	0.0	20	3	900	4.7	0.52
4	0.0	25	4	1200	4.9	0.34
5	0.5	10	2	900	3.5	0.27
6	0.5	15	1	1200	3.8	0.67
7	0.5	20	4	300	3.8	0.39
8	0.5	25	3	600	3.4	0.42
9	1.0	10	3	1200	3.1	0.49
10	1.0	15	4	900	2.7	0.51
11	1.0	20	1	600	3.4	0.56
12	1.0	25	2	300	3.6	0.58
13	1.5	10	4	600	2.7	0.37
14	1.5	15	3	300	2.1	0.39
15	1.5	20	2	1200	3.9	0.43
16	1.5	25	1	900	3.4	0.46

Table 4
Analysis of variance table (Epoxy/MWCNT).

(a) Specific wear rate

Source	DF	Seq SS	Adj MS	F	P
A	3	78.522	26.17	58.92	0.004
B	3	1.881	0.627	1.41	0.392
C	3	3.451	1.150	2.59	0.228
D	3	8.84	2.948	6.64	0.077
Residual error	3	1.33	0.442		
Total	15	94.03			

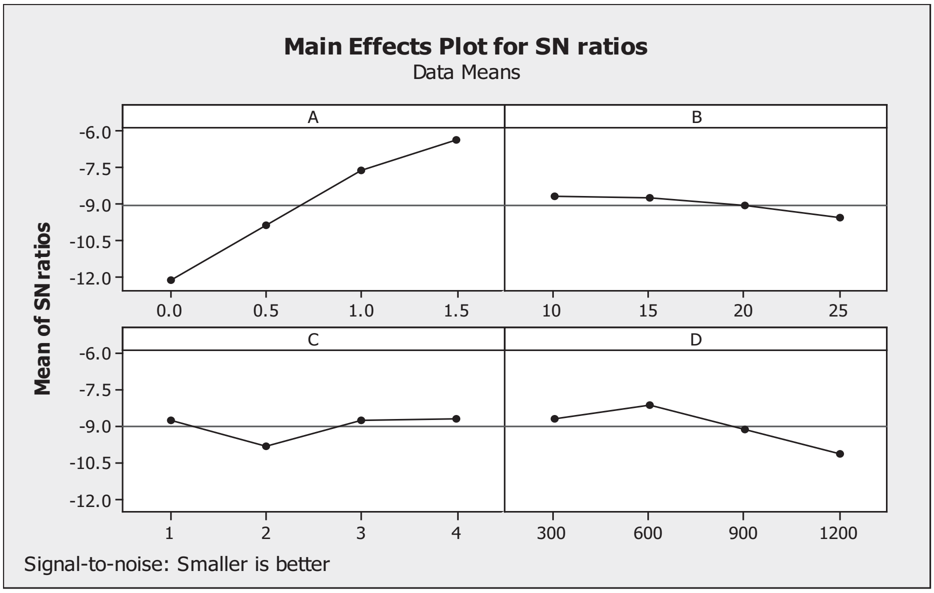
(b) Friction coefficient

Source	DF	Seq SS	Adj MS	F	P
A	3	116.28	38.76	198.7	0.001
B	3	0.67	0.2233	1.14	0.457
C	3	0.703	0.2344	1.2	0.442
D	3	7.365	2.451	12.57	0.033
Residual error	3	0.585	0.195		
Total	15	125.59			

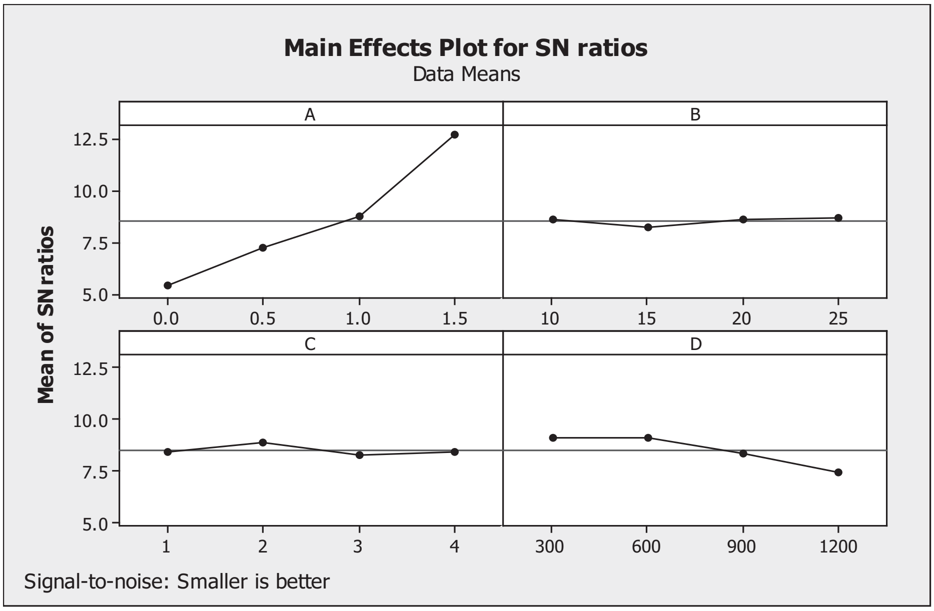
to determine the significance of process parameters on the performance characteristic. This is accomplished by separating the total variability of the responses, which is measured by the sum of the squared deviations from the total mean of the responses into contributions by each variable and the error.

3. Results and discussion

To evaluate the statistical significance of different parameters like Percentage of reinforcement, Sliding distance (m), Sliding velocity (m/s) and Normal load (N) on friction coefficient and specific wear rate for E-glass-epoxy/MWCNT composite, ANOVA is carried out on testing data using MINITAB. Tables 4 and 5 illustrate the ANOVA results with the friction coefficient and wear. This study is conducted for 5% significance level of confidence. The p-values less than 5% represent that the main effects are more significant. The effect of percentage of MWCNT on the wear rate and friction coefficient is depicted in Fig. 1. Percentage of reinforcement, Sliding distance, Sliding velocity and Normal load have comparatively less significant contribution on friction coefficient (Fig. 2). The similar trend can be observed in the wear results E-glass-epoxy/MWCNT composite (Table 5). From these tests, it is proven that the sliding wear properties of MWCNT E-glass/epoxy samples are different from MWCNT/epoxy. From ANOVA, it was noticed that at 95% confidence

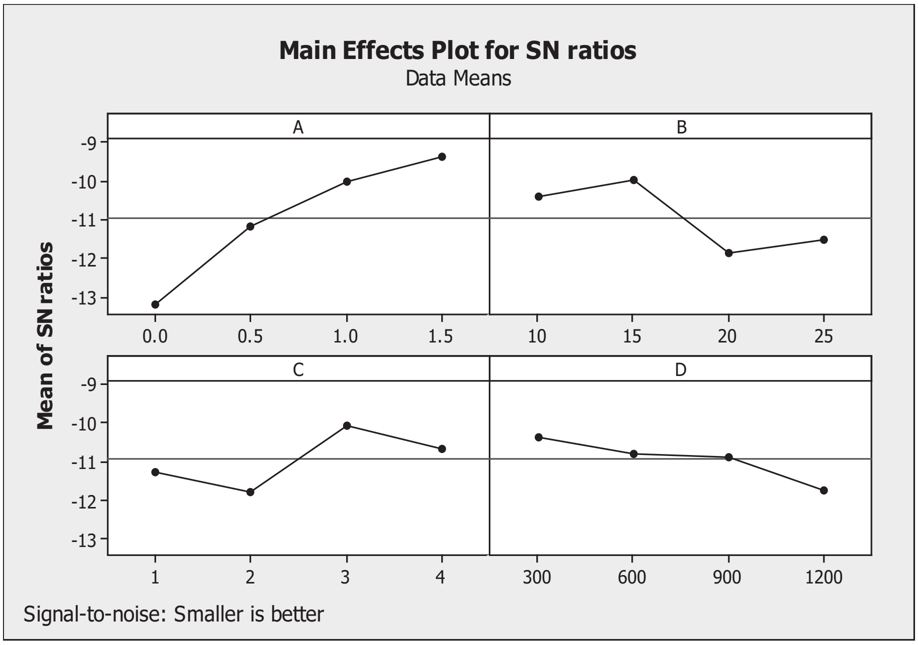


(a) Specific wear rate

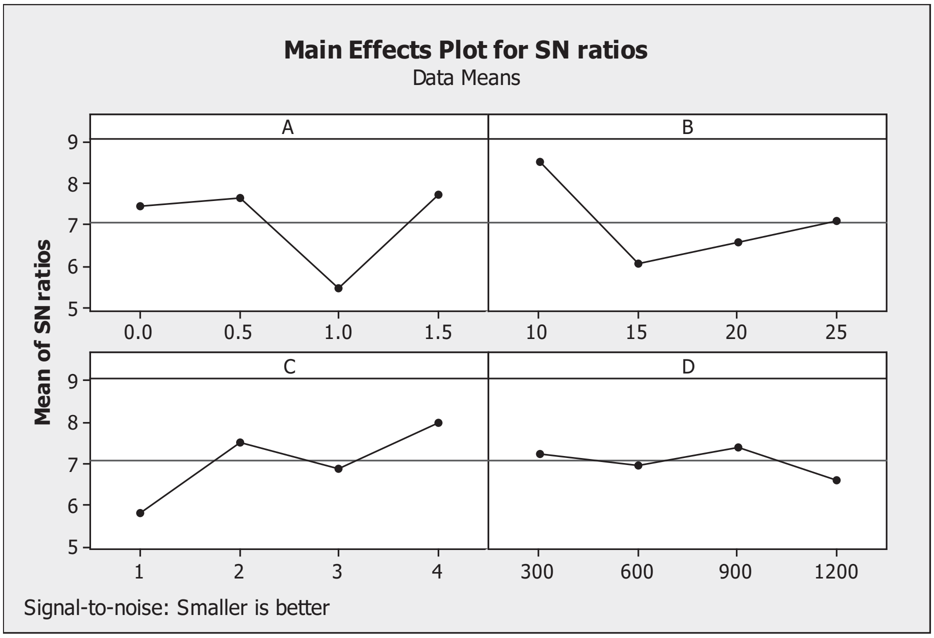


(b) Friction coefficient

Fig. 1. Main effects plot (Epoxy/MWCNT).



(a) Specific wear rate



(b) Friction coefficient

Fig. 2. Main effects plot (E glass-Epoxy/MWCNT).

level ($P < 0.05$), percentage of reinforcement has a significant effect on specific wear rate and friction coefficient. Confirmation tests have been conducted to validate the results (Table 6) obtained by Taguchi technique.

It is obvious, for both types of composites (Epoxy–MWCNT and E-glass-epoxy/MWCNT) that the wear loss decreases with increase of percentage of MWCNT. It specifies that a stronger interaction between epoxy and MWCNTs has an enormous effect on the wear resistance, particularly at a higher (1.5% wt) percentage of MWCNT. Figure 2 depicts the influence of percentage of MWCNTs on the friction coefficient. The reduction in the friction coefficient is attributed to the lubricating effect of MWCNTs in the epoxy resin. Figure 3 demonstrates that the wear track surface of epoxy resin is uneven. With the addition of MWCNTs to the resin, the abrasive wear on the worn surface is considerably decreased. This represents that addition of MWCNTs is an efficient way to reduce abrasion wear and to enhance the wear resistance of Epoxy–MWCNT composite. Figure 3 shows the Scanning Electron Microscope (SEM)

Table 5
Analysis of variance table (E glass-Epoxy/MWCNT).

(a) Specific wear rate

Source	DF	Seq SS	Adj MS	F	P
A	3	33.33	11.1	17.46	0.021
B	3	9.806	3.26	5.14	0.106
C	3	6.441	2.14	3.37	0.172
D	3	4.172	1.39	2.19	0.269
Residual error	3	1.909	0.63		
Total	15	55.66			

(b) Friction coefficient

Source	DF	Seq SS	Adj MS	F	P
A	3	14.009	14.009	0.85	0.55
B	3	13.77	13.77	0.84	0.556
C	3	10.948	10.948	0.67	0.626
D	3	1.547	1.547	0.09	0.958
Residual error	3	16.419	16.419		
Total	15	56.693			

pictures of the worn surfaces for 0, 0.5, 1 and 1.5 wt% MWCNT filled epoxy. These pictures clearly show that Epoxy/MWCNT composite exhibits considerable adherences. These adherences might be due to the better attraction between the MMT layers and the epoxy. Fracture studies of composites have been performed by undertaking scanning electron microscopy (SEM).

Figure 4 demonstrates the worn surfaces of a specimen from the E-glass/epoxy (0.5 wt. % MWCNT) composite. The failure of the specimens was mainly due to matrix crushing and fiber fracture. These observations substantiated the improvement in specific wear rate. Microscopic investigation of worn out sample fracture surface revealed that fiber debonding (Fig. 4) happens when the stresses at the fiber matrix interface exceed the interfacial strength, causing the fiber to debond from the matrix. Debonding takes place as a result of failure commenced at a point in the fiber/matrix interface through the length of the interface. Microscopic investigation of worn out sample fracture surface has also revealed that fiber debonding and fiber pullout happen when the stresses at the fiber matrix interface exceed the interfacial strength, causing the fiber to debond from the matrix. Fiber fracture was found in the E-glass/epoxy of 0.5 wt. % MWCNT composite. Conversely fiber fracture followed by fiber pullout, debris formation was examined in the E-glass/epoxy of 1 wt. % MWCNT composite. The pure epoxy resin has a wear track wider and deeper showing a higher amount of material removal and more abrasive wear. Morphology results support the wear loss results and reveal that damage to fiber and matrix is increased with an increase in the applied normal load. In both cases, severe damage to fiber and matrix was observed at a higher load, whereas at lower applied normal loads, only a loss of matrix from the composite surface was noticed. Specific wear rate increased as the sliding speed increased. Variations of specific wear rate with sliding velocity 2 m/s and sliding distance 600 m under various loads are shown in Fig. 2. With reference to the figure, it is noticed that

Table 6
Results of the confirmation experiments.

Performance responses	Optimum set of parameters	Predicted optimum value	Experimental optimum value
Specific wear rate (mm^3/N-m)			
E glass-Epoxy/MWCNT	A4-B2-C3-D1	2.3×10^{-6}	2.1×10^{-6}
Epoxy/MWCNT	A4-B1-C4-D3	2.6×10^{-4}	2.2×10^{-4}
Friction coefficient			
E glass-Epoxy/MWCNT	A4-B1-C2-D1	0.37	0.4
Epoxy/MWCNT	A4-B1-C2-D1	0.21	0.23

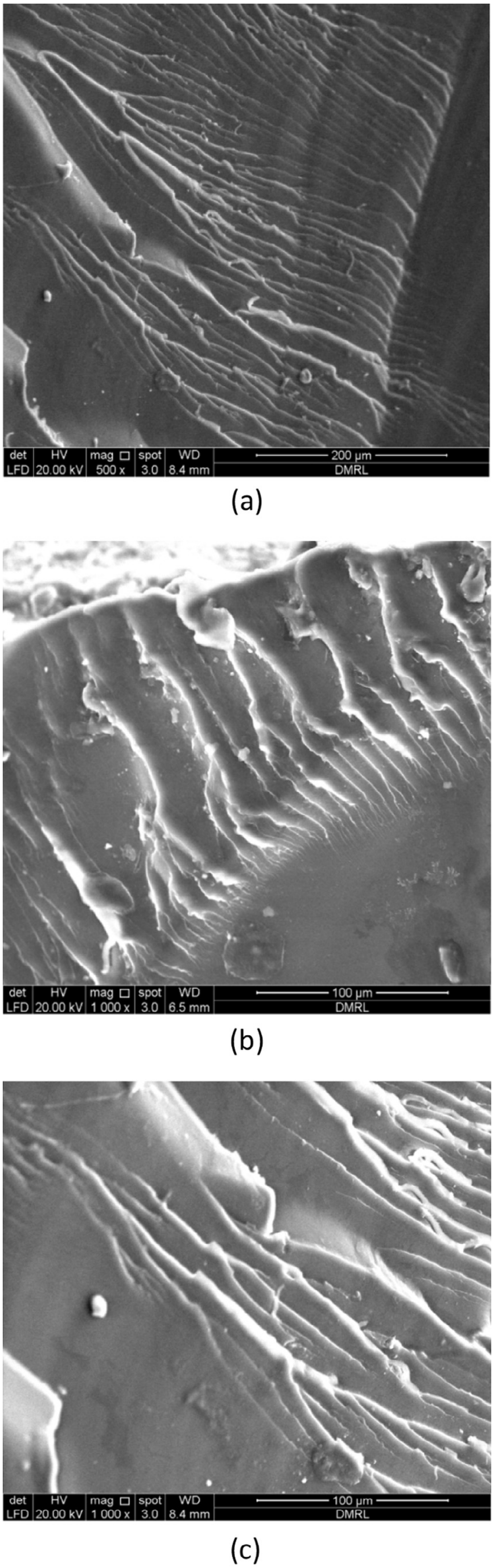


Fig. 3. SEM micrographs of the worn surfaces of different specimens. (a) Pure epoxy and (b, c) 0.5% MWCNTs/epoxy at 15 N normal load and 900 m sliding distance.

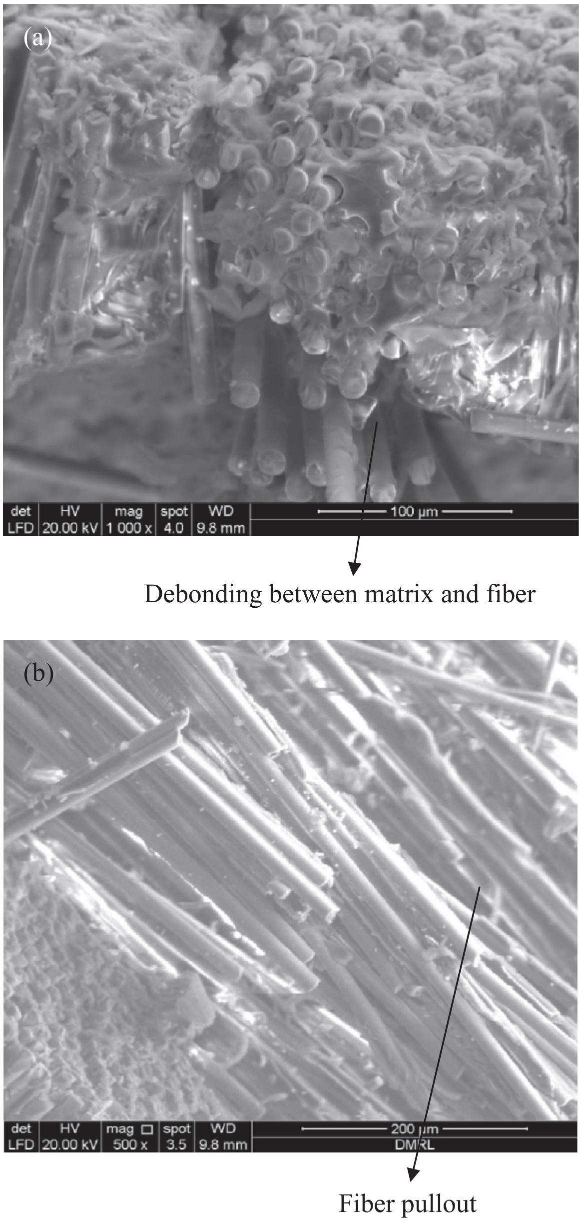


Fig. 4. SEM images of E-glass-epoxy/MWCNTs.

the specific wear rate of the composites is seen to be high at the applied load of 15 N. On increasing the applied load to 25 N the specific wear rate drops down considerably, indicating a change in wear process. The specific wear rate appears to be minimal at 60 N and then rises again with increasing applied load. This is because during the initial run in period when epoxy comes in contact with the counter surface, severe abrasive wear occurs and the specific wear rate increases. Further the specific wear rate is controlled by glass fiber reinforcement. At lower loads, the shear forces that develop due to the sliding action overcome the weak van der Waals forces of attraction between the MWCNT, which are present in the epoxy matrix. These detached MWCNTs spread over the sliding surface, thereby reducing the direct contact between the composite surface and the steel disc. Hence, they protect the specimen surface from further wear. As the load increases, the matrix starts deforming, and then it detaches from the fiber surface and gets trapped in between the sliding surfaces. This hard debris enhances further wear of the composites. At higher loads, the debris detached from the specimen surface creates a layer that consists of a mixture of epoxy and MWCNT, between the sliding surfaces. This helps reduce wear at higher loads [17,18]. During the sliding process, fibers bear the majority of applied pressure. Consequently, interfacial fatigue occurs in some regions where fibers are highly loaded and interface debonding takes place. In addition, when fibers are highly loaded, fiber cracking occurs when fibers could not transfer the applied stress efficiently and the maximum stress in the fibers exceeds their strength. Besides, the difference between the modulus of the polymer matrix and fibers leads to stress concentration at matrix/fiber interface. A typical wear scar obtained at different loading conditions is shown in Fig. 4. As observed from Fig. 4 it exhibits the highest wear among all applied loads due to less fiber to support the matrix and the severe cutting mode of abrasive wear that occurred, which results in deep grooves that are clearly visible in the micrograph. It is clear from the micrograph that the only mechanism that causes wear at this condition is wedge formation mode of abrasive wear; this can be attributed to the fact that there is comparatively good adhesion between the fiber and matrix which in turn results into low wear rate. Surface morphology reveals the fact that the wear takes place due to ploughing and debris entrapment mechanism; this results in mitigating the wear resulting in low wear rate. Micrographs show the existence of ploughing and wedge formation which is characterized by wear due to plastic deformation and results into moderate wear rate [18]. Micrographs show the matrix damage and subsequent matrix removal due to the formation and propagation of microcracks as well as macrocracks at the surfaces. The absence of any plastic deformation or grooves formation is due to the inherent brittle nature of E-glass fiber, hence the contributing wear mechanism should be fracture of the surface. The optimum control variables have been derived to reduce both wear and friction coefficient of composites. The combination of factors $A_4B_1C_4D_3$ and $A_4B_1C_2D_1$ offers minimum specific wear rate and friction coefficient for epoxy–MWCNT composites. Conversely, combination of factors $A_4B_2C_3D_1$ and $A_4B_1C_2D_1$ offers minimum specific wear rate and friction coefficient for E glass-epoxy/MWCNT composites.

4. Conclusions

The following conclusions are drawn:

1. The inclusion of MWCNTs to the epoxy matrix considerably enhances its sliding wear behavior. Percentage of reinforcement has only significant effect on specific wear rate and friction coefficient in both these composites.
2. It is clear, for both types of composites (Epoxy–MWCNT and E-glass-epoxy/MWCNT) that the specific wear rate decreases with increase of percentage of MWCNT.
3. Microscopic investigation of worn out sample fracture surface has also revealed that fiber debonding and fiber pullout happens when the stresses at the fiber matrix interface exceed the interfacial strength, causing the fiber to debond from the matrix.
4. The optimum control variables have been derived to reduce both wear and friction coefficient of composites.
5. The ANOVA results reveal that Sliding distance, Sliding velocity and Normal load are less significant for both Epoxy/MWCNT composites E glass-epoxy/MWCNT composites.

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