Indian Journal of Engineering & Materials Sciences
Vol. 29, December 2022, pp. 779-787
DOI: 10.56042/ijems.v29i6.70309

An experimental assessment of abrasive wear behavior of GNP/Carbon fiber/epoxy hybrid composites

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Received: 9 September 2022; Accepted: 17 October 2022

This investigation has evaluated the wear properties of Carbon fiber-epoxy/GNP (Graphene Nanoplatelets) composites. In this research, carbon fiber and Graphene nanoplatelets (GNP) of different weight percentages of GNP (0, 0.1,0.3, and 0.5 wt.%) reinforced hybrid composites were fabricated via compression molding assist hand layup technique. An abrasive wear test has been performed using the Design of experiments. Analysis of variance (ANOVA) tables has been used to understand the effect of control parameters (wt.% of filler, normal load, and sliding distance) on response parameters (specific wear rate and friction coefficient). The control variables such as normal loads of 5, 10, 15, and 20 N and sliding distances (150, 200, 250, and 300 m) are selected for this study. It has been discovered that adding GNPs reduces the particular wear rate and friction coefficient. Scanning electron microscopy (SEM) was used to examine composites' worn surfaces. The composites with GNPs had lower weight loss, friction coefficient, and wear rate as compared to plain carbon fiber-reinforced epoxy, and these metrics decreased as the percentage of GNPs increased. The analysis concluded that experimental results are closer to optimum results.

Keywords: Abrasive wear, Carbon fiber, Epoxy, Graphene nanoplatelets (GNP), Scanning electron microscopy (SEM)

1 Introduction

In recent years polymer matrix composites (PMC) have been more popular than metal matrix composites due to their light-weight, low cost, and easy processability. Thermoset polymer composites are applied mainly in automotive, structural components, aerospace, sport, and chemical industries[1–3]. Automobile components and industrial equipment are increasingly made of hybrid fiber-reinforced polymer composites and widely utilized in applications that require abrasion resistance[4,5] In addition, polymer composites reinforced with woven fiber have better wear properties[6]. Due to their greater physical and mechanical qualities, mainly carbon-based filler and fiber-based composites, are being investigated as prospective predicted materials for diverse tribological usage[7,8]. The addition of GNP lowered the wear volume loss in the GFRP composites from a tribological viewpoint. Furthermore, a considerable amount (1 wt.%) of GNP improved the composite materials' tribo- mechanical performance significantly[9]. Ultrahigh molecular weight polyethylene and MoS_2 fillers improve load-bearing applications' mechanical and tribological properties [10].

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The influence of multi-wall carbon nanotubes and graphene oxide nanosheets on the tribological characteristics of epoxy composites is investigated[11]. These studies revealed that functional fillers such as carbon nanofiller and inorganic nanofillers significantly impact wear characteristics. Many different model of wear calculated wear rate as a function of weight percent of filler, mechanical qualities, normal load, etc.[12–14].The researchers' experiments revealed that the abrasive wear behavior of polymer composites was impacted by many operating variables such as normal load, sliding distance, and grain size of abrasive paper [15–17]. The previous wear models and experimental investigations have one major flaw: they do not account for the impact of specific parameters on composite abrasive wear. The Traditional methods can investigate the effect of particular elements on single response situation optimization. However, in tribological situations, multiple response optimization is required[18,19]. The majority of the following findings are based on woven fabric reinforced polymer composites that are either randomly oriented or unidirectionally orientated.

The current study is unique because it intends to analyze the abrasive wear performance of

GNP/Carbon fiber reinforced epoxy composites. Multi-pass abrasive wear is widespread in real-world applications. Currently, there is limited work on the phenomena of abrasive wear in multi-pass settings[9,20–23]. The investigation findings could lead to a rise in the use of GNP/Carbon fiber-reinforced epoxy composites. ANOVA and Taguchi's method is implemented to determine the best parameters for various outputs such as specific wear rate (W) and coefficient of friction (COF).

2 Materials and Methods

2.1 Experimentation

Thermosetting epoxy (LY-556) and hardener (HY-951) were bought from Go Green Products, India. Bidirectional carbon woven fabric of 200 GSM (grams per square meter) and fibers of about 6–8 µm diameter were obtained from Go Green Pvt. Ltd, India. Graphene nanoplatelets (GNP) were used as a secondary reinforcement obtained from Sisco Research Laboratories Pvt. Ltd., India. Epoxy is mixed with GNP/acetone solution, and this solution was put on the magnetic stirrer at 300 rpm for 20 minutes. Then speed was increased to 500rpm for another 10 minutes to get a homogeneous mixture of GNP and epoxy. The temperature of the magnetic stirrer was maintained at 75°C for the complete removal of acetone. After this bath ultrasonicator of 30kHz was used in ice-cooled water for mixing and proper dispersion of nanoparticles in epoxy for one hour. Then furnace was used at 60°C for 10 minutes then remove off the remaining acetone in the mixture. A curing hardener was added to the mixture at room temperature in a ratio of 10:1. After cooling at room temperature, the hand layup technique was used for making laminated composites of eight layers of carbon fabric. Then the die was placed in the compression molding machine under the 25KN load for 24 hours. Table 1 shows the designation of all the samples and the shore hardness of composites. After the curing sheet (150mm X 150mm X 4mm) was removed and cut, the samples from the prepared sheet. The schematic diagram of the fabrication process has shown in Fig. 1.

Table 1 — Composites designation with measured physical properties

Materials	Designation	Density	Shore-D Hardness
Neat carbon fiber/Epoxy	CEG-0	1.42	82
0.1% GNP/Carbon fiber/Epoxy	CEG-1	1.39	85
0.3% GNP/Carbon fiber/Epoxy	CEG-2	1.36	88
0.5% GNP/Carbon fiber/Epoxy	CEG-3	1.33	90

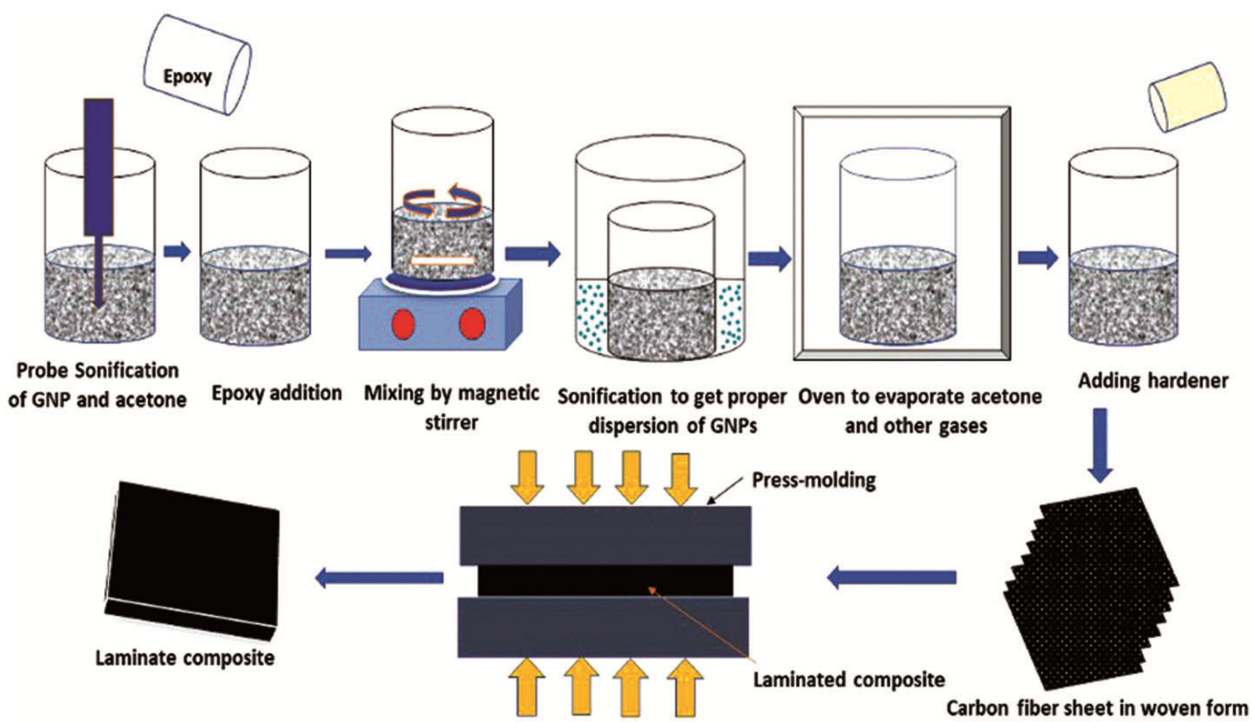

Fig. 1 — Schematic presentation of fabrication process.

2.2 Abrasive wear test

The abrasive wear performance[9,13] of different composites was investigated using a pin-on-disc machine using waterproof SiC (220 grits size) paper from DUCOM, Bangalore, India. A diamond cutter was utilized to cut 10 mm x 10 mm square specimens from composite laminates for standard. These composite specimens were tested according to the ASTM G99 attached to a 30 mm long aluminum pin with a diameter of 10 mm. After that, the specimen and pin assembly were attached and abraded using SiC paper (1500 grit) to achieve homogeneous surface contact. The experiment was revised three times, and the average value was taken to calculate the wear loss. The following operating parameters were used to explore the effect of abrading distance: variable load: 5, 10, 15, and 20N, and abrading distances of 150, 200, 250, and 300 m were used with the constant sliding velocity of 200 rpm. The disc was cleaned with acetone before the test. The tests were carried out using different parameters listed in Table 2. Electronic balance (Citizen CX 265 Model) is used to determine the specimen's weight. The ratio of wear loss to the product of normal load and sliding distance was used to calculate the W. The COF was observed using data from the device.

2.3 Design of experiments: Taguchi method

The input parameters chosen based on preliminary investigations were: the percentage of filler, normal load (N), and sliding distance (m). Table 3 shows the operating range of input parameters and the levels used. This method employs two essential tools: (i) the S/N ratio to assess the quality and (ii) orthogonal arrays to adopt several elements impacting tribological performance simultaneously. From Table 3, an L16 orthogonal array was adopted according to the Taguchi quality design principle[15–19,24]. Minitab statistical software was used to create all of the designs, graphs, and analyses in this study. Depending on the sort of characteristics, different S/N ratios are available. 'Smaller is better' refers to a property where a lower value indicates more outstanding performance [18]. The influence of input parameters on the W and COF of GNP-filled carbon fiber/epoxy composites was studied statistically. ANOVA is used to analyze the impact of input parameters on the evaluation of tribological characteristics such as W and COF.

Table 2 — Levels of input parameters

Parameters	Level 1	Level 2	Level 3	Level 4	Units
Percentage of filler (C)	0	0.1	0.3	0.5	%
Normal load (F)	5	10	15	20	N
Sliding distance (L)	150	200	250	300	m

2.4 SEM Examination

The morphology of worn surface composites was analyzed by scanning electron microscopy using an EV018 setup. Gold coating using a sputter coater (model: JEOL JFC 1600, USA) was done on the top surface of the sample before imaging.

3 Results and Discussion

3.1 Wear characteristics analysis

ANOVA is performed on testing data using MINITAB to determine the significance of various parameters such as percentage of filler, normal load, and sliding distance on W and COF for Carbon fiber-epoxy/GNP composite. The signal-to-noise ratios (S/N) serve as optimization objective functions[18], assisting in data analysis, predicting the best outcomes, and considering the mean and inconsistency of the experimental outcome[19]. The S/N ratio of W and COF parameters independently. It indicates that factor (concentration) has the most significant impact on the response variable (W and COF). Similarly, sliding speed has the most negligible impact on particular wear rates and COF. The purpose of this study is to reduce wear loss and improve the quality of manufactured hybrid composites by hand layup, compression molding, and validation testing using the Taguchi method. The means and S/N ratio plots for W and COF for various control parameters for two-body abrasive wear are shown in different Figures. In those graphs, the influence of the GNP weight percent on the W and COF is projected.

Table 3 — Experimental design using L16 orthogonal array

Exp. no.	Percentage of filler (C)	Normal load (F)	Sliding distance (L)	Specific wear rate(mm^3/N-m) x 10^{-11}	Coefficient of friction
1.	0	5	150	2.2	0.50
2.	0	10	200	2.0	0.52
3.	0	15	250	1.9	0.55
4.	0	20	300	1.75	0.59
5.	0.1	5	200	1.71	0.43
6.	0.1	10	150	1.62	0.47
7.	0.1	15	300	1.54	0.48
8.	0.1	20	250	1.50	0.49
9.	0.3	5	250	1.41	0.37
10.	0.3	10	300	1.34	0.39
11.	0.3	15	150	1.40	0.40
12.	0.3	20	200	1.28	0.41
13.	0.5	5	300	1.12	0.31
14.	0.5	10	250	0.98	0.34
15.	0.5	15	200	0.88	0.35
16.	0.5	20	150	0.80	0.36

Examining these statistics makes it possible to optimize the control elements that result in the least wear loss. Figure 2 shows GNP filler of 0.5 wt.%, a load of 20 N, and a sliding distance of 150 m resulting in the least amount of wear at 220grit size abrasive paper. Figure 3 shows that a factor combination of GNP filler of 0.5 wt.%, the load of 5 N, and a sliding distance of 300 m result in the lowest COF.

The experimental analysis concluded that specific wear rates fall as the sliding distance increases. The specific wear rate falls for all specimens rubbed with abrasive paper as the abrading distance increases. Interestingly, all composites demonstrated the highest specific wear rate during the initial abrading distance (150 m) compared to the other increased distances. It confirms that the wear track is incompletely formed and that the sharpness of SiC particles is still present [15,25]. A specific wear rate significantly decreased as the successive abrading distance increased. With increased abrading distance, the sleek wear track creation and blunt particle of SiC could be due to a steady decrease in specific wear rate. However, CEG-0 had a greater specific wear rate, which dropped dramatically when GNP added up to 0.5 %. The highest decrement in particular wear rate was recorded when the composite was reinforced with 0.5 wt. % of GNP. 0.5% GNP composite has the lowest specific wear rate about 44 % lower than CEG-0 composite under identical conditions. It should be noted that the use of GNP as a filler improved a variety of mechanical properties. GNP acts as authentic reinforcement to prevent SiC particles from penetrating the epoxy matrix and carbon fibers from being pulled out due to their superior mechanical capabilities. According to the current work, higher stickiness between matrix and carbon fiber, GNP film deposition on abrasive paper, and a change in the tribo-couple contact could explain the better tribological capabilities of GNP-filled composites[26,27].

3.2 ANOVA prediction and analysis

ANOVA was used to assess the statistical significance of various control factors. The ANOVA results for abrasive wear for W and COF are shown in Tables 4 and 5. The ANOVA was performed using a 5% level of significance. The significance level is indicated in the last column of the ANOVA table. The major effects are more significant when the p-values are fewer than 5%. According to ANOVA, the weight

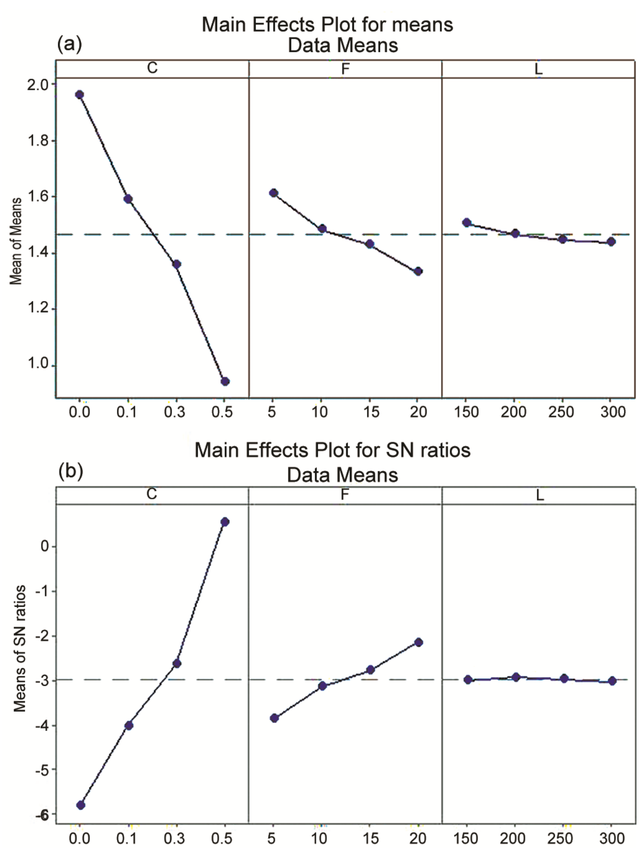

Fig. 2 — Main Effect plot for (a) Means, and (b) S/N ratios for W.

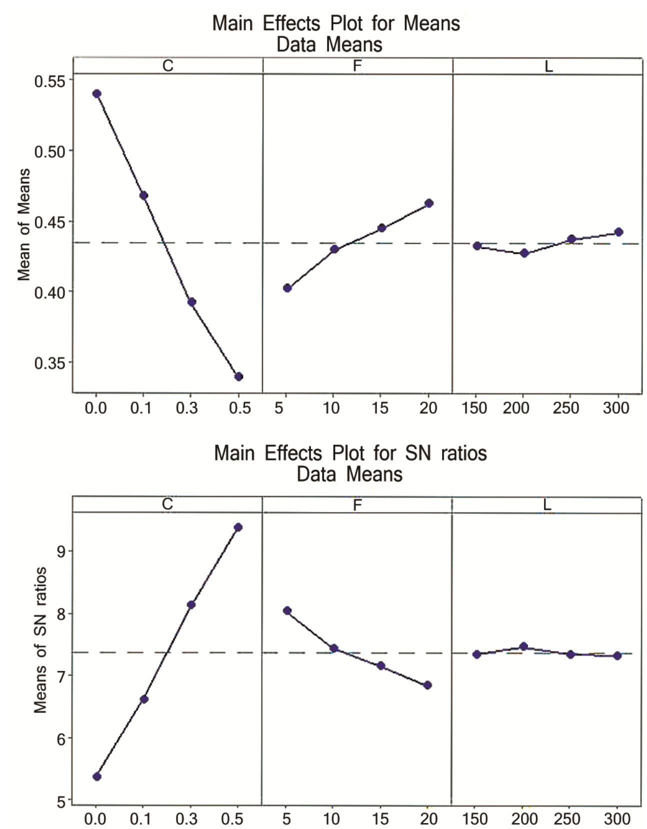

Fig. 3 — Main Effect plot for (a) Means, and (b) S/N ratios for COF.

Table 4 — Analysis of variance table (W)

Source	DF	Seq SS	Contribution (%)	Adj MS	F-Value	P-Value
C	3	2.18287	91.58	0.727623	149.32	0.000
F	3	0.16082	6.75	0.053606	11.00	0.007
L	3	0.01067	0.45	0.003556	0.73	0.571
Error	6	0.02924	1.23	0.004873		
Total	15	2.38359	100.0			
S		R-sq		R-sq(adj)		R-sq(pre)
0.0698063		98.77%		96.63%		91.28%

Table 5 — Analysis of variance table (COF)

Source	DF	Seq SS	Contribution (%)	Adj MS	F-Value	P-Value
C	3	0.488118	91.76	0.162706	404.95	0.000
F	3	0.040790	7.67	0.013597	33.84	0.000
L	3	0.000645	0.12	0.000215	0.53	0.675
Error	6	0.002411	0.45	0.000402		
Total	15	0531963	100.0			
S		R-sq		R-sq(adj)		R-sq(pre)
0.0200448		99.55%		98.87%		96.78%

percent of filler has a considerable effect on W and COF at the 95 percent confidence level[25,27]. Specific wear rate load is highly considerable with a p-value of 0.000, followed by normal load (p = 0.007) and sliding distance (p = 0.571) according to ANOVA data. Finally, the least considerable factor is the sliding distance with a p-value of 0.571. For COF, the least considerable factor is also sliding distance with a p-value of 0.675. According to table 4, the first-factor concentration contributes the most to wear loss or particular wear rate, accounting for 91.58 percent of the total. While the other factors show less effect. Although the factor sliding distance has generated just 0.571% contribution. At the 5% level of significance, two parameters, percent of filler and normal load, are meaningful, whereas the remaining components are negligible. The applied load shows the highest contribution for specific wear rate and COF. Similarly, the higher the C-value, the larger the impact of that factor on W, and vice versa. Obviously, for GNP/Carbon fiber/Epoxy hybrid composites, with increasing weight percent of GNP wear rate reduces. It was emphasized that a stronger connection between epoxy, carbon fiber, and GNP has a large impact on wear, especially at 0.5 percent of GNP. The lubricating effect of GNPs in the hybrid composite is responsible for the lower friction coefficient. In summary, the ANOVA findings show that percentage of GNP has the greatest and least influence on W and COF for the sliding distance in the current article.

Equation (1) and (2) is regression equation that describes the link between wear rate and numerous input parameters.

Regression Equation-1

$$W^{0.5} = 1.4919 - 0.8031C - 0.00742F - 0.000086L \quad \text{...(1)}$$

Regression Equation-2

$$\frac{-1}{COF} = -2.1061 - 2.1452C + 0.02101F - 0.000223L \quad \text{... (2)}$$

Where W is the specific wear rate in $mm^3/N\text{-}m$, C is the weight percentage of filler, F is the load in N, and L is the sliding distance in m. Equations (1) and (2) can estimate the anticipated values of wear rate and COF by combining multiple input parameters. However, with the L16 orthogonal array, observed values have resulted in Table 3. The residual (observed error) is the discrepancy between observed and expected values. As a result, plotting the residual curve is required to interpret the observed further and predicted values, i.e., residual curves can be used to analyze the data.

Figures 4 and 5 show the different residual plots for W and COF, and the histogram shows that the residual range is 0.06 to 0.06 for W and -0.08 to 0.08 for COF. The histogram also shows that the frequency is the second most significant for zero residual, implying that equation (2) best fits the observed values. The plot shows the residual on the y-axis and the estimated response on the x-axis. Non-linearity, uneven error variances, and outliers can all be seen in this graph. The normal probability plot reveals that the majority of the data is contained within the curve, which better predicts the observed values[15,16]. Furthermore, both axes are symmetrical, implying that the provided model accurately represents the obtained results. Furthermore, in all residual plots, the variability of a variable is the same across the range

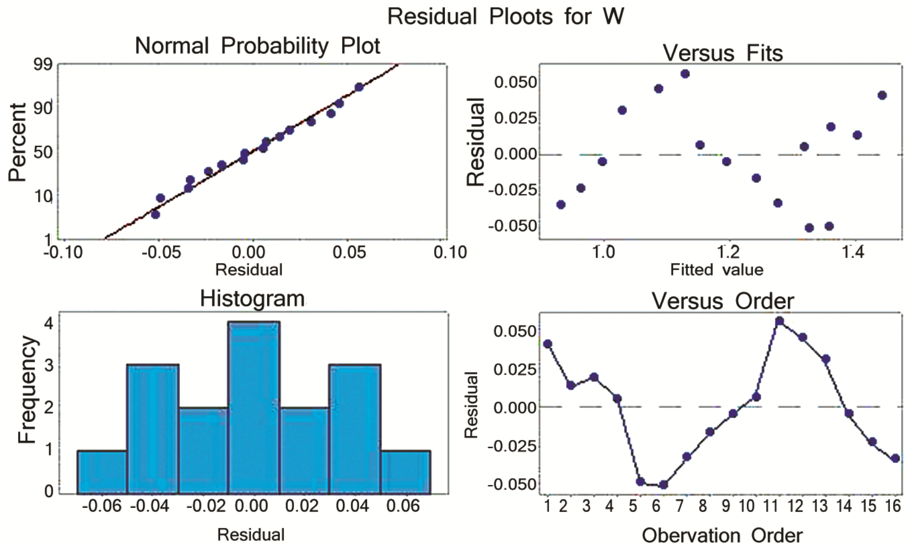

Fig. 4 — Residual graph for W.

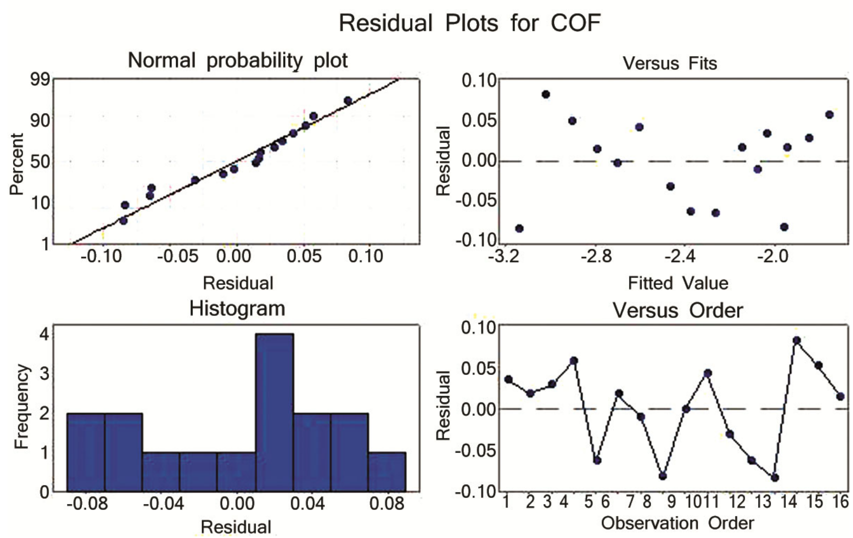

Fig. 5 — Residual graph for COF.

of values that predict it. As a result, the best-fitting model for understanding the observed values in this investigation is the current regression equation (1) and (2) models.

3.3 Contour plots

Contour plots are used in this study to investigate the potential association between three process parameters. The contour plots of wear rate with a 3D connection in 2D are shown in Fig. 6 (a)–(b). In the plot x and y variables (predictors) showed on the x and y-axes and W (response values) showed on Z-axis. The dark green zone shows a higher value of W, which is small area-wise. The contour planes illustrate numerous types of wear loss regions, which are represented by distinct colors. Wear rates larger than 2 mm^3/Nm were seen at longer sliding distances, higher loads, and lower concentrations, but not in the area (Fig. 6(a)–(b)). The presence of 0.5 percent GNP reinforcement in the matrix has a lubricating effect, boosting wear resistance. Although, due to the filler at larger concentrations and greater sliding distances and load, a small area of wear rate of less than 1 mm^3/Nm has been recorded. All contour plots show varied quality scores in the contour domain. Furthermore, the presence of non-linear contour layers implies a substantial interaction between the variables. Again, the various contour graphs show a noticeable disparity in W versus process parameters. The contour area also indicates that all factors have an interaction impact.

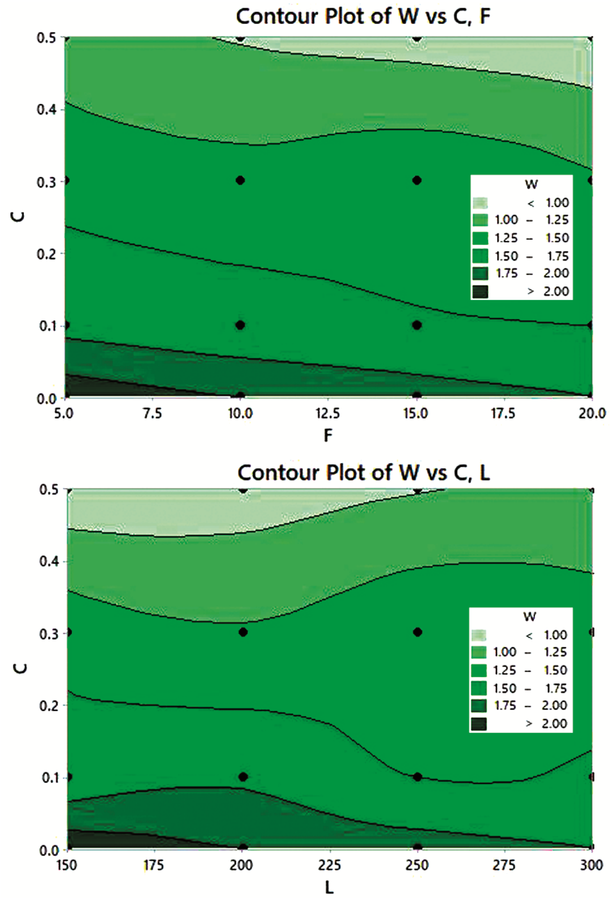

Fig. 6 (a-b) — Contour graphs of W for different combinations of parameters.

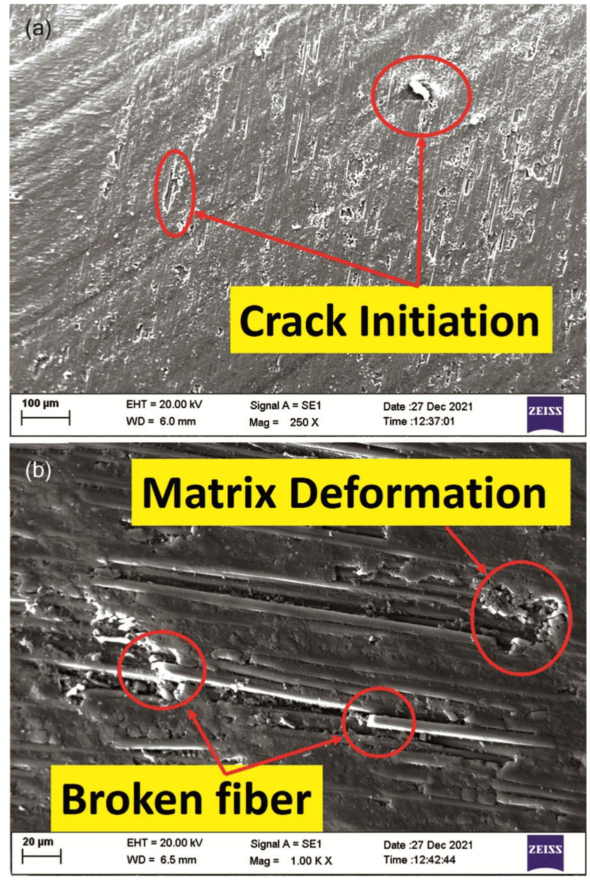

Fig. 7— SEM images of worn surfaces CEG-0.

Moreover, the higher the disorder in plots, the higher the interaction[16]. Additionally, contour plots denote the area encircled by the various wear rate scores.

3.4 Surface morphology

The worn surfaces of different hybrid composite samples contain different weight percent (0 and 0.5) of GNP shown in Figs 7 and 8. This indicates that adding GNPs to a GNP/Carbon fiber/Epoxy composite effectively reduces abrasive wear and improves wear resistance. The specimens failed primarily due to matrix deformation and fiber fracture. When the stresses at the fiber-matrix interface are more than interfacial strength, fiber cracking[20,22] is generated, shown in Fig. 7. Debonding results from a failure that started at one point in the fiber/matrix interface and continued along its length. Fiber fracture and matrix formation were found in the carbon fiber/ epoxy (CEG-0) composite. Conversely, agglomeration of particles and fiber pullout was seen in the 0.1% GNP/carbon fiber/epoxy composite. The wear track on the pure epoxy resin is broader and more profound, indicating more material loss and abrasive wear. The wear loss results are supported by morphology findings, which show that damage to fiber and matrix increases as the applied normal load increases. At higher loads, substantial fiber and matrix damage was seen. Matrix deformation has occurred at lower applied loads. The figure shows that the W of composites is higher at 5 N. When the load is increased to 20 N, the W decreases significantly, indicating a change in the wear phenomena. At 20 N, the W appears to be modest, but it rises again when the applied load increases. Substantial abrasive wear occurs in the early running period when epoxy comes into contact with the surface, and W increases at that period. Carbon fiber reinforcing also regulates the W. Due to sliding action at lower loads, the weak van der Waals forces between the GNPs in the epoxy matrix are overcome by shear forces[9]. GNPs that had become dislodged dispersed throughout the sliding surface, minimizing direct contact between the composite and paper surfaces. As a result, they shield the specimen's surface from additional damage shown in Fig. 8. The matrix begins to distort as the stress increases to a

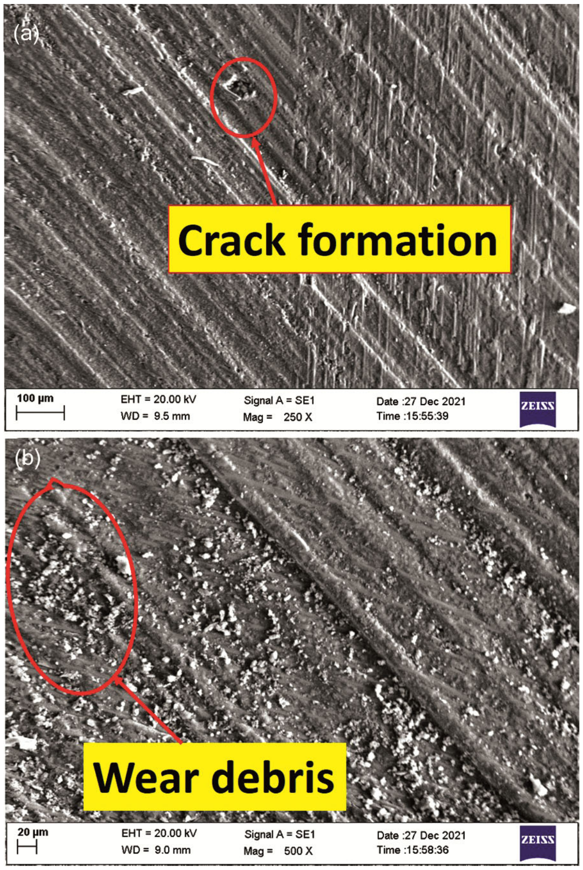

Fig. 8 — SEM images of worn surfaces CEG-5.

certain level, and the fiber is detached from the matrix. The composites are subjected to more wear due to the hard debris. At higher loads, debris dislodged from the specimen surface forms a layer between the sliding surfaces consisting of a mixture of epoxy and GNP. This aids in the reduction of wear under higher loads. Most of the applied pressure is carried by the fibers during the sliding phase. As a result, interfacial fatigue and interface debonding occur in areas where fibers are heavily pressured. Figure 8 shows a typical wear scar generated under various loading circumstances, showing the highest wear among all applied loads. SEM images show a large crack that is an indication of fiber fracture. The fiber and matrix have relatively strong adhesion, resulting in a low wear rate. As surface morphology demonstrates, wear is caused by ploughing and debris entrapment mechanisms, resulting in wear mitigation and a low wear rate. Ploughing and wedge formation can be seen on micrographs, responsible for a moderate wear rate[9,28].SEM images depict matrix degradation and removal due to the creation and spread of micro and macrocrack at the surfaces. The optimal control variables for reducing composite wear and friction coefficient have been determined.

Table 6 — Result analysis via experimentation

Performance responses	Optimum parameters	optimum value (predicted)	optimum value (experimental)
W (mm^3/Nm)	C4-F4-L2	9.25×10^{-12}	9.67×10^{-12}
COF	C4-F1-L2	0.32	0.34

3.5. Optimum conditions prediction and validation of results

The optimum values of each factor are listed in Table 6, and the confirmation test was performed using a set of optimum parameters. For GNP/Carbon fiber/epoxy composites, the combination of variables C4F4L2 and C4F1L2 provides the lowest specified wear rate and friction coefficient. Following that, three sets of experiments are carried out using this set of control parameters. Their wear rate values are determined. The experimental value of W and COF is closer to the predicted value. There is only 4.5% and 6.2% difference between the predicted and experimental results of W and COF. It has been observed that the predicted and experimental values are closer to each other.

4 Conclusion

It has the following conclusions:

- The addition of GNPs to the carbon fiber-reinforced epoxy composites improves the sliding wear behavior significantly. In each composite, the filler weight percent has a greater effect on the W and COF.
- The specific wear rate and COF for GNP/Carbon fiber/epoxy composites lowers as the percentage of GNP increases.
- Fiber pullout and cracking occur when stresses at the interface of matrix and fiber exceed the interfacial strength, according to the microscopic examination of worn-out sample fracture surfaces.
- The optimal control variables for reducing composite wear rate and COF have been determined. According to the ANOVA results, the sliding distance and applied load are less prominent for GNP/Carbon fiber/epoxy composites.

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