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Research article

Taguchi and Regression Analysis of Abrasive Wear Behavior of Carbon Epoxy Composite

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A B S T R A C T

This study aimed to assess the abrasive wear performance of a composite material made of carbon epoxy and graphite particles. The experiments were conducted on Abrasion Test rig and examined the weight loss of the composite material, taking into account the sliding distance and normal load. Taguchi method is employed to study the effect of process parameters on composite wear. Multiple regressions were utilized to establish a correlation between wear and wear parameters. The findings indicated that weight loss increased with higher applied loads, sliding distances, and weight fractions of graphite filler. Finally, the experimental results were validated through confirmation tests.

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1. INTRODUCTION

Polymer composites (PMCs) are gaining popularity as favorable materials in tribological and structural applications. They offer high strength, stiffness, good chemical resistance, and easy to process, making them useful in all industrial applications. With the growing use of PMCs, it is important to better understand their behavior under different working conditions.

Epoxy is a thermoset polymer common matrix material used for structural composites. However, inclusion of right fillers and reinforcements can improve the performance of epoxy-based composites. Carbon fiber is a commonly used reinforcement material in composites, particularly in the aerospace, automotive, and leisure industries. Carbon fiber offers good mechanical properties, making it useful in developing new industrial applications. Abrasive wear is the process by which hard asperities move across a softer surface under load and the material is removed from the softer surface, resulting in grooves [1]. There is a limited data on the study of abrasive wear behavior of PMCs [2, 3]. Therefore, it is essential to have a comprehensive understanding of their abrasive wear characteristics.

In a study conducted by Feng Hua Su et al. [4], the effect of adding nano Al2O3 and Si3N4 particulate fillers to Carbon fabric/phenolic

composites on tribological behavior was investigated. The researchers found that the addition of particulate fillers improved the tribological behavior. This was due to the increased interfacial bonding strength and improved mechanical strength resulting from the addition of the fillers. M Savitha et al. [5] conducted a study on tribological behavior of glass-vinyl ester composites with and without SiC fillers. They found that filled composites had greater wear resistance than the unfilled composites. In a study by Thomas Larsen et al. [6], tribological properties of epoxy based composites reinforced with carbon aramid and glass fiber were investigated. They observed that the coefficient of friction (COF) is less for glass fiber composite and the wear rate was higher. Suresha et al. [7] also conducted similar study of unfilled and graphite filled glass-epoxy composites. They stated that the filled composite exhibited higher wear resistance compared to unfilled ones. B. Shivamurthy et al. [8] investigated the friction and wear behavior of glass-epoxy composites filled with SiO2 fillers. They found that composites filled with 6 and 9 weight % of SiO2 particulates exhibited a steady wear rate and high wear resistance. In a study conducted by S R Chauhan et al. [9], the tribological behavior of fly ash-filled glass vinylester composites was investigated. The results demonstrated that the incorporation of fly ash significantly reduced the COF and improved the wear resistance. The authors suggested that the frictional and wear behavior of composites can be effectively described by a factorial design of experiment. In another study, S Basavarajappa et al. [10] investigated the tribological behavior of SiC and graphite particulate filled glass epoxy composites. The outcomes indicated that the presence of SiC and graphite particles substantially enhanced the wear resistance of the composites. The authors also employed Taguchi method to predict the tribological properties.

The literature contains a wealth of information on the tribological behavior of composites. However, the tribological properties are not only determined by material properties, but are also influenced by other parameters like normal load, sliding distance, fiber fraction, and orientation. Many studies have been conducted to investigate the effect of these parameters on the wear rate of polymer composites. Researchers have successfully used the Taguchi approach to study the wear behavior of PMCs.

The present study aims at investigating the wear behavior of graphite-filled carbon epoxy composites. To determine the significance of control factors that affect the wear rate, the study uses Taguchi design of experiments technique. By using this method, the aim is to analyze the impact of several factors on the wear rate of the composites, and to optimize the performance characteristics of the material.

2. EXPERIMENTAL

Bidirectional plain-woven carbon fabric reinforced epoxy composite was fabricated for the study. To improve the properties of the composites, graphite particulates were added as fillers.

The composite samples were prepared by hand lay-up technique and then subjected to compression molding. Three samples were prepared with different weight fractions of graphite filler in the composite. Table 1 shows the details of the fabricated composites.

Table 1. Composite samples.

Sample	Matrix	Reinforcement	Filler
A	38 % Epoxy	60% Carbon Fabric	2 % Graphite
B	36 % Epoxy	60% Carbon Fabric	4 % Graphite
C	34 % Epoxy	60% Carbon Fabric	6 % Graphite

The wear studies were conducted using the dry sand rubber wheel abrasion test setup in accordance with the ASTM G65..The tests were conducted for various sliding distances and loads.

Prior to testing, the samples were weighed to determine their initial weight before being mounted in the sample holder. The silica sand abrasive with 200-μm particle size was then introduced between the rubber wheel and the test sample. The experiments were conducted at three normal loads and three abrading distances as presented in Table 2. The amount of wear was determined by measuring the weight loss of the test samples.

Table 2. Levels of variables.

Control parameters	Level		
	I	II	III
Filler Content % (A)	2	4	6
Normal Load N (B)	11	23	35
Sliding distance m (C)	300	600	900

In order to obtain data in a controlled manner, a plan of experiments was conducted using Taguchi technique. Process parameters' influence on the wear behavior was investigated using analysis of variance (ANOVA). Taguchi approach was able to identify the influence of control factors and their interactions on the wear rate.

The experimental observations were transformed into a signal-to-noise (S/N) ratio to evaluate the performance of the composite materials. In this study, the S/N ratio for minimum wear rate was used, which is a smaller-is-better characteristic. The calculation of the S/N ratio for this characteristic is expressed by the following equation:

$$\frac{S}{N} = -10log\frac{1}{n}(\Sigma {y_n}^2). \quad (1)$$

where 'n' is the number of repeated trials and y1,y2,...,yn represent the response values of the wear rate characteristic.

3. RESULTS AND DISCUSSIONS

The wear rate and S/N ratio of the experimental data is given in Table 3. To predict the performance measure, the potential interactions between the control parameters were taken into consideration.

Table 3. Abrasive wear test results.

S. No.	Filler Content	Normal Load	Sliding Distance	Wear	S/N
1	2	11	300	0.0788	22.06948
2	2	11	600	0.1646	15.6714
3	2	11	900	0.1909	14.38388
4	2	23	300	0.275	11.21335
5	2	23	600	0.3301	9.62709
6	2	23	900	0.4872	6.245854
7	2	35	300	0.4502	6.93189
8	2	35	600	0.6888	3.238137
9	2	35	900	0.7192	2.863006
10	4	11	300	0.0829	21.62891
11	4	11	600	0.1428	16.90544
12	4	11	900	0.245	12.21668
13	4	23	300	0.2531	11.93416
14	4	23	600	0.4312	7.306425
15	4	23	900	0.5972	4.477604
16	4	35	300	0.4051	7.848755
17	4	35	600	0.6116	4.27065
18	4	35	900	0.8326	1.591272
19	6	11	300	0.0821	21.71314
20	6	11	600	0.1675	15.5197
21	6	11	900	0.2221	13.06903
22	6	23	300	0.3092	10.19521
23	6	23	600	0.6823	3.320493
24	6	23	900	0.6388	3.892702
25	6	35	300	0.5959	4.496532
26	6	35	600	0.6942	3.170308
27	6	35	900	0.8354	1.562111

Table 4. ANOVA table.

Source	DF	SeqSS	AdjSS	AdjMS	F	P	Percent Contribution
A	2	13.97	13.967	6.983	5.55	0.031	1.32
B	2	814.65	814.646	407.323	323.57	0.000	77.03
C	2	192.76	192.76	96.38	76.56	0.000	18.23
A*B	4	6.62	6.616	1.654	1.31	0.343	0.63
A*C	4	5.74	5.74	1.435	1.14	0.404	0.54
B*C	4	13.77	13.77	3.442	2.73	0.105	1.30
Residual Error	8	10.07	10.071	1.259			0.95
Total	26	1057.57					100.00

To determine the statistical significance of the control parameters and their interactions on the wear rate, ANOVA was conducted. Table 4 displays the ANOVA results, and the last column of the table indicates the percentage contribution of the specific control factors and their potential interactions. Percent contribution is the ratio of SeqSS of corresponding parameter to the total SeqSS.

The ANOVA results as shown in Table 4 indicates that the wear rate is significantly influenced by the normal load with 77.03 % contribution, followed by sliding distance (18.23 %) and filler content (1.32 %). Among the potential interactions, the interaction between sliding distance and normal load has more impact (1.3 %), followed by the interaction between filler content and normal load (0.63 %).

The response table displays the average S/N ratio for each level of every factor, along with ranks based on Delta statistics, which is the difference between the highest and lowest values. Upon examination of response table 5 it is evident that the normal load has the highest rank, followed by sliding distance and filler content. This is in line with the ANOVA result.

Table 5. Response table.

Level	A	B	C
1	10.249	17.02	13.115
2	9.798	7.579	8.781
3	8.549	3.997	6.7
Delta	1.701	13.023	6.414
Rank	3	1	2

Figure 1 (a) present the impact of the control factors on the wear rate of the composites. A main effects plot depicts the response mean for each factor level linked by a line. The slope of the line indicates the magnitude of the main effect on the wear rate.

The level with the maximum value of the S/N ratio's mean for each control factor produces the minimum wear rate. In this instance, the results analysis indicates that, the combination of A1, B1, and C1 gives the lowest wear rate. This indicates that using 2% filler, with 11N load and 300m distance, will result in a minimum wear rate.

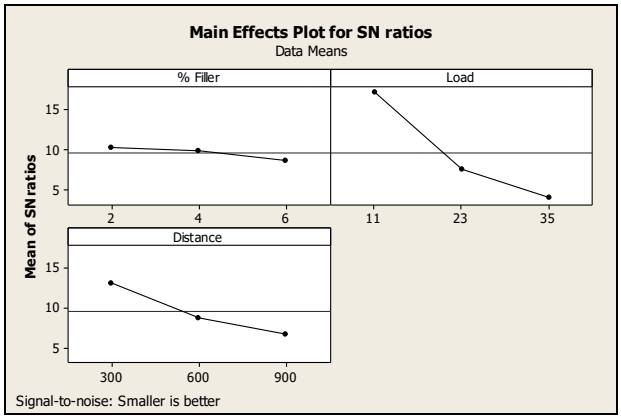


Fig. 1 (a). Main effects plot.

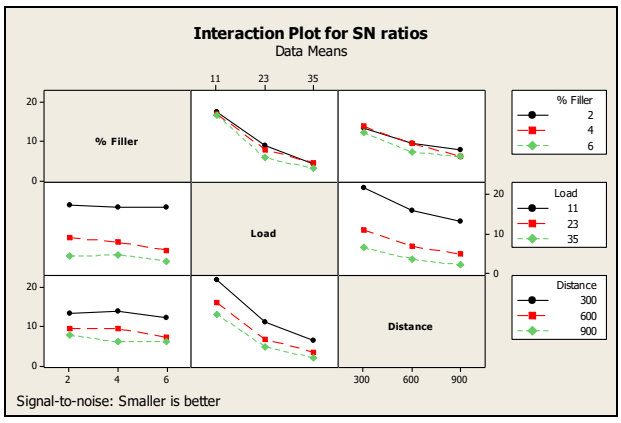


Fig. 1 (b). Interaction plot.

An interaction plot can be utilized to visualize possible interactions when one factor's effect is dependent on the level of the other factor. The interaction plot is depicted in Figures 1(b). It is evident from this figures that the interaction AxB, has a significant effect on the wear rate.

3.1 Confirmation test

Final step is confirmation experiment, aimed at validating the inference drawn during the analysis phase. The new set of factor settings A1, B1, C1 is used to predict the wear rate. The predicted value is calculated using Equation (2),
Predicted value

$$\hat{\eta} = \eta_m + \Sigma_{i=0}^{o}(\eta_1 - \eta_m) \quad (2)$$

η_m- total mean S/N ratio, $\bar{\eta}i$- mean S/N ratio at the optimal level, o- no. of parameters that considerably affect the wear.

The resulting equation appears to be capable of calculating the wear rate to a satisfactory level of accuracy, with error of 1.5% (Table 6). This confirms the statistical approach adapted is accurate.

Table 6. Confirmation experiments results.

	Prediction	Experimental
S/N Ratio	21.732	22.0695
% Error	1.5%	

3.2 Regression analysis

To establish the relationship between wear parameters with wear rate, a linear regression model was employed. The generalized regression equation used is represented as follows:

$$Y = a0+a1xA+a2xB+a3xC \quad (3)$$

Here, Y represents the wear weight loss, while A, B, and C denote the filler content, normal load, and sliding distance and coefficients a1, a2, a3 correspond to the variables A, B, C respectively. After determining the coefficients, the final linear regression equation is developed. The constants are computed using the linear regression analysis method. Substituting these coefficients into equation (3) yields the following regression equation shown in equation (4)

$$Wear = -0.401 + 0.0234 \cdot A + 0.0206 \cdot B + 0.000414 \cdot C \quad (4)$$

Correlation coefficient (R^2)=92.1%

The higher the R^2, the better the equation fits the data. Therefore, the high R^2 values confirm the appropriateness of the equations used and the accuracy of the determined constants.

4. CONCLUSION

The current study investigated how the inclusion of graphite filler affects the wear behavior of composites. From the results following conclusions were drawn:

- The Taguchi method was successful in analyzing the wear behavior of the composites with the test variables filler content, normal load, and sliding distance.
- Factorial design of experiments was effective in describing the wear performance of the composites and developing linear equations to predict wear rate under specific conditions.
- The main effects plot showed that the combination of A1, B1, C1, corresponding to 2% graphite filler, 11 N load, and 300m sliding distance, resulted in the minimum wear rate.
- he interaction plot showed that the interaction of percent filler and normal load, had a substantial influence on the wear rate.
- The regression coefficient obtained with the regression value ranging from 88.5% to 92.1% indicated a satisfactory correlation between the experimental and predicted wear rate.

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