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Wear Behavior Evaluation of Natural Fibre Composite Using Taguchi Technique

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Abstract: In this work, the Taguchi technique was used to analyze the wear characteristics of produced basalt fibre reinforced composites. The produced samples were tested for wear in a dry sliding state at room temperature against abrasive disc using a typical pin-on-disc machine. The wear tests were performed at 1000, 2000, 3000, and 4000 m of sliding distance and at a speeds of 500, 1000, 1500, and 2000 rpm. The design of experiments (DOE) strategy was used to evaluate wear behavior in the presence of variable factors such as sliding distance, speed, and material composition. The signal-to-noise ratio and analysis of variance (ANOVA) were also employed to investigate the effect of these characteristics on wear loss. The particular wear rate is greatly influenced by the material type, speed, and sliding distance, which are 40.90%, 34.56%, and 24.11%, respectively. A multiple linear regression equation has been established, and the confirmation test error ranges from 1.96% to 10.93%.

Keywords:Composite Material, Basalt fibre, Abrasive wear, Taguchi technique, ANOVA.

1. Introduction

Composite materials have a significant role in everyday activities due to their wide variety of desired qualities, in comparison to conventional materials. Fibre reinforced composite materials have a wide range of uses, including aerospace structures, automotive goods, energy, and the building sector, as well as maritime engineering, electrical and chemical packaging[1)]. As the world recognises its degradation rate, eco-friendliness, and richness, evolving natural fibre polymer composites have gained acceptance into a range of technical fields[2)]. They have a high potential for replacing and competing with existing synthetic fibres[3-4)]. Out of the different extant natural fibres, the basalt fibre, recognized as a 21st century material, has a good influence on polymer-based composites. When particularly in comparison to glass fibre, which is generally included in structural composites for industrial applications[5)], basalt is a natural material found in volcanic rocks that has superior mechanical behavior, outstanding thermal firmness, improved chemical permanence, excellent moisture inertness, resistance to abrasive wear and friction, and can easily be recycled[6-7)]. Basalt fibres have the unique property of not becoming hazardous when exposed to air or water[8)]. These favorable features point to prospective uses of basalt fibre in domains where glass fibre composites are presently widely used[9)]. The most prevalent kind of igneous rock, basalt, makes up more than 90% of all volcanic rocks. The structural and morphological characteristics of basalt rocks are significantly influenced by the pace at which volcanic lava begins to cool. Silicon dioxide (SiO2) is the principal chemical ingredient of basalt. Due to the higher SiO2 content, basalt fibre delivers exceptional mechanical and chemical stability. Because to the incorporation of CaO, MgO, and TiO2, basalt fibres offer high thermal stability and oxidation resistance. Due to its superior mechanical potency, dimensional consistency, and chemical inertness, epoxy resin has risen to the top of the list of popular matrices used in the manufacture of sophisticated composites[10)]. When the load increases, the bonding between the fibre and matrix deteriorates due to the rising flash temperature, leading to the easy ripping or peeling off of the basalt fibres and the wear recalcitrance of the composites to decline[11)]. Composite materials with collective effects are created when numerous mixed foreign components are incorporated within an organic binder like resin[12)]. The examination of composite materials' tribological and mechanical properties has become increasingly significant. Strength, creep effectiveness, and wear resistance are all enhanced when a reinforcement phase is added to a matrix13). By increasing basalt fibre content, tensile strength improved while specific wear rate dropped. The dry sliding wear behaviors of basalt short fibre reinforced composites revealed that the inclusion of basalt fibres lowered the composites' friction coefficient14). Using nanofillers increases mechanical and tribological properties, as well as adhesion between the fibres and the matrix 15-19). Because of their superior performance and Elevated properties, glass fibres are the most typically employed in big composite constructions. Carbon fibres are stronger and stiffer than glass. Unfortunately, the cost of these carbon fibres is far higher than that of glass fibres, making constructions composed solely of carbon fibre prohibitively expensive. Manufacturers are drawn to the usage of alternative materials that are more practical from a design standpoint and may also be cost-effective without compromising structural performance20). The interval between carbon and E-glass fibre reinforced polymer composites is filled by the use of basalt fibre21). Polymer-based composites have the constraint of stress relaxation and creep in prolonged deployments. Carbon nanofibres mixed to resins make them less susceptible to stress relaxation22). To analyze the wear behavior of produced composites and anticipate wear versus service circumstances23), a statistical tool using Taguchi method design of trials can be used. This study employed an analytical techniques relying on the Taguchi and ANOVA methodologies to assess the influence of each input characteristic on the variance of wear loss of the manufactured composite material. To portray the link between input characteristic and wear behaviour, paradigmatic frameworks have been generated.

2. Materials and Experimental Details

2.1 Materials

The basalt fabric-plain of 200 GSM used as reinforcement, provided by Nickunj Eximp Enterprises Private limited, Mumbai, India. Lapox L12 is a medium viscosity liquid epoxy resin and K6 hardener supplied by MechStore, Bengaluru, India. Hand layup technique was used to prepare basalt fibre reinforced composite. The composite laminates were fabricated and cured.

The cured laminates were cut to yield wear test specimen according to ASTM G99 standard. The details of composite specimen prepared are given in Table 1.

Table 1.Details of basalt fibre/epoxy composite specimen

Sample	S1	S2	S3	S4
Reinforcement and matrix (%)	30:70	40:60	50:50	60:40
Total weight of the composite (g)	600	600	600	600
Reinforcement (g)	180	240	300	360
Matrix (g)	420	360	300	240
Weight of each laminate (g)	20	20	20	20
Number of laminate	9	12	15	18

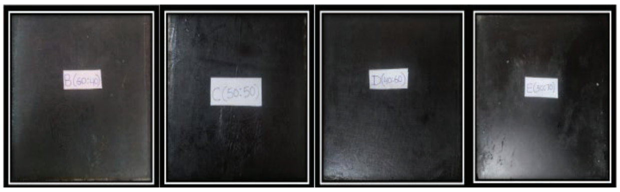


Fig.1: Fabricated composite sample

2.2 Dry Sliding Wear Test

The wear behaviour of the specimens was studied according to ASTM G99 standard using pin-on-disc wear test setup with a fixed load of 10 N, a time frame of 600 seconds, and a range of speeds. Figure 2 shows the DUCOM TR20LE pin-on-disc test setup. The samples with a square cross section of 10mm x 10mm x4 mm were attached with glue to a stainless steel pin of 30mm long such that the contact surface was parallel to the laminate's plane as shown in Fig. 3. The main objective of the work is to evaluate wear behavior of the fabricated composite in the presence of variable factors such as sliding distance (1000, 2000, 3000, and 4000m), speed(500, 1000, 1500, and 2000rpm), and material composition (S4, S3, S2, S1). Three variables are being tested at four distinct levels using an L16 orthogonal array (16 tests, 3 variables, 4 levels). The influence of material type, speed, and sliding distance on wear rate were examined by a quantitative method Taguchi and ANOVA approaches based on "Smaller is better".

Fig.2: Wear test setup

Fig.3: Wear tested specimens

To achieve consistent contact with the revolving disc, the specimen contact surface was polished. After completing the requisite sliding distance, the samples were cleaned, and their weights were examined with an electronic scale with a 0.1mg precision to calculate the weight loss. The weight difference of specimen before and after the test determines the weight reduction.

3. Taguchi Technique

In order to ascertain the level of significance of each process input variable on the range of wear loss of the composite material, a quantitative method based on Taguchi and ANOVA approaches was used. The relationship between the process variables and its wear behavior has been modeled mathematically. In order to get the best outcomes with the fewest possible trials, the Taguchi approach is employed to build the trial for the abrasive wear research. In the experimental plan put forth by Genichi Taguchi, orthogonal arrays are used to arrange the process-affecting variables and the levels at which they must be systematically changed in order to complete the experiment with the minimal number of trials possible rather than trying every possible combination[24)].

The optimisation approach comprises studying the outcome based on the compositions, computing the coefficients, suited the observational evidence, forecasting the outcome, and analyzing the fit of the fitted model. The independent variables for the composites were applied load and sliding distance, whereas the response variable was wear rate.

3.1 Plan of Experiments

After determining the control parameters, their levels, and responses, as indicated in Table 2, an orthogonal array was built. Three variables are being tested at four distinct levels. Using an L16 orthogonal array, we carried out a Taguchi experiment (16 tests, 3 factors, 4 levels). Here, various sliding distance, speed, and material type factors are taken into consideration for analysis.

Table 2.Control factors and their levels

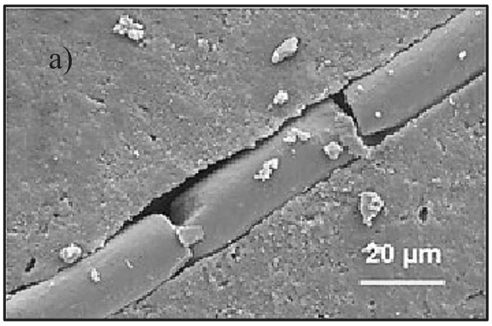
Level	1	2	3	4	Units
Control factors					
Sliding distance (A)	1000	2000	3000	4000	m
Speed (B)	500	1000	1500	2000	rpm
Material Type (C)	60% BF	50% BF	40% BF	30% BF	none

Table 3.Experimental wear results of different compositions of composite specimens in L16 orthogonal array with mean wear loss

Sliding Distance (m)	Speed (rpm)	Material type	Wear loss (mg)
1000	500	S4	9.1
1000	1000	S3	11.3
1000	1500	S2	12.4
1000	2000	S1	16.5
2000	500	S3	10.9
2000	1000	S4	9.46
2000	1500	S1	15.3
2000	2000	S2	12.7
3000	500	S2	11.8
3000	1000	S1	14.7
3000	1500	S4	9.62
3000	2000	S3	12.5
4000	500	S1	14.3
4000	1000	S2	12.1
4000	1500	S3	10.7
4000	2000	S4	9.8

3.2 Statistical Analysis

Wear loss analysis was performed using the MINITAB application. Taking into consideration the different components, the S/N correlation was computed as the effect for the material's wear loss. The S/N correlation and reaction for each component are developed against each of its degrees, with a smaller-the-better criterion for wear loss, as illustrated in Fig. 5. Based on an analysis of the data, it can be deduced that when the amount of the factor increases, the mean material loss due to wear as a result of abrasion also increases[25)]. Wear loss rises approximately linearly as increasing with the parameter[26)] sliding distance (A), speed (B), and material type (C). A scanning electron microscopy (SEM) used to investigate the worn surfaces of composites. In Figure 4(a)-(c), the presence of grooves in different sizes were observed repeatedly on the worn surfaces, linked to the process of delamination. Abrasive damage the fibers and matrix, de-attachment of fibers from resin the preferential propagation of subsurface cracks along the sliding direction, giving rise to the detachment of wear particles in the form of flakes.



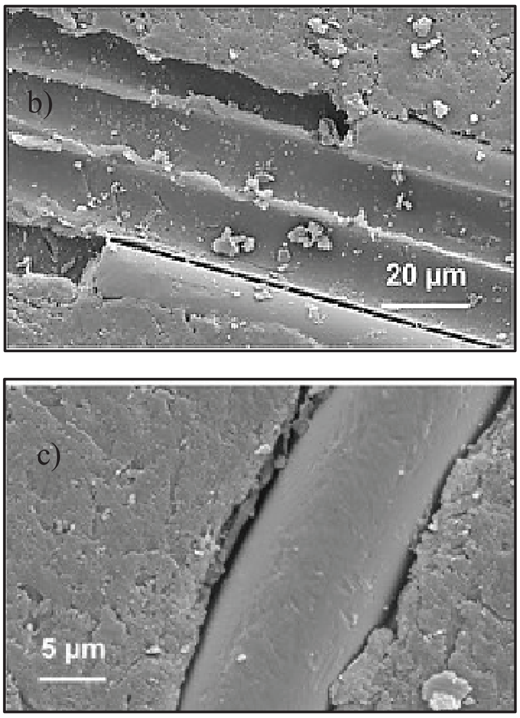


Fig.4: The SEM microstructure of the worn surfaces

In terms of wear reduction, factors A, B, and C have a major influence; a blend of A1, B1, and C1 results in the least amount of wear. An additional statistical study, such as analysis of variance, is required to justify the components and their importance.

The response graphs made it extremely simple to find the optimal testing settings for these control elements. The graphs depict the change in the S/N ratio when the control factor setting was altered from one level to the next. The response graphs with larger S/N values had the best specific wear rate.

Table 4.S/N response table (Smaller is better)

Level	Sliding Distance (A)	Speed (B)	Material type (C)
1	-21.62	-21.12	-23.62
2	-21.46	-21.35	-21.76
3	-21.55	-21.60	-21.28
4	-21.49	-22.05	-19.45
Delta	0.15	0.93	4.17
Rank	3	2	1

Table 5.Response Table for Mean

Level	Sliding Distance (m)	Speed (rpm)	Material type
1	12.325	11.525	9.395
2	12.040	11.840	11.600
3	11.975	12.875	15.200
4	11.975	12.875	15.200
Delta	0.350	1.350	5.805
Rank	3	2	1

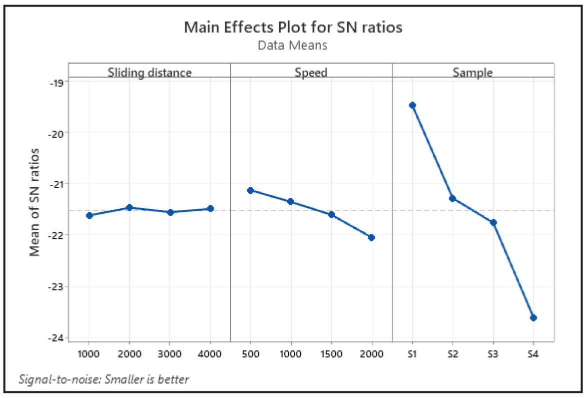


Fig.5: Main effects plot for S/N ratios

Fig.6: Main effects plot for means

Table 6.Analysis of Variance for fabricated composite material

Source	DF	Adj SS	Adj MS	F-Value	P-Value	P% (Contribution)
Sliding distance	3	14.0925	7.04625	58.44	0.013	24.11
Speed	3	20.1940	10.097	81.77	0.011	34.56
Sample	3	23.8984	11.9492	96.59	0.010	40.90
Error	6	0.244	0.122			0.417
Total	15	58.4289				100

S = 0.29471 R-Sq = 99.51% R-Sq(adj) = 98.65%

DF: degrees of freedom; Seq SS: sequential sum of squares; Adj SS: adjusted sum of squares; Adj MS: adjusted mean squares

3.3 Analysis of Variance

An analysis of variance (ANOVA) is performed in including the Taguchi method to assess the effect of each process parameter on wear loss. ANOVA can be used to calculate the proportion benefit of numerous process parameters to a given measurable statistic. Table 7 displays the ANOVA findings when the analysis is performed with a 95% confidence level. Factors having p-values below 0.05 were taken into account to have influenced quantitative significance to the execution assessments. The proportion of benefaction of every factors is shown in Table 6, and it is found that the sample has the greatest impact on wear loss is 40.90%, accompanied by sliding distance and speed. When S/N correlations are taken the speed and sliding distance have influences of 34.56% and 24.11%, respectively. As a result, the composition of the specimen's reinforcement to matrix is a crucial parameter to consider during abrasive wear, followed by speed and duration.

Wear Loss = -11.125+0.000098 × Sliding distance + 0.000088 × Speed -------- (1)

S = 0.0412975 R-Sq = 97.6% R-Sq(adj) = 95.4%

The characteristics indicated in Table 7 were used in the confirmation test. Table 8 displays the outcomes of a correlation amid the estimated results from the dataset provided in this study (Equation 1) and the data generated empirically. The determined inaccuracy for wear loss ranges from 1.96% to 10.93%, according to the examination of the cited table. As a result, with a fair degree of approximation, the aforementioned multiple regression model connects the assessment of the wear of the manufactured composite material.

Table 7.Parameter used in the Confirmation test

Test	Sliding Distance (m)	Speed (rpm)	Material type
1	1000	1000	S2
2	3000	500	S2
3	4000	1500	S3

Table 8.Parameter used in the Confirmation test

Test	Experimental value	Regression model	% error
1	11.8	10.787	10.93
2	10.7	10.601	1.96
3	11.3	10.939	6.36

The Taguchi confirmation test is employed to evaluate test results and assess the validity of the study. Table 9 illustrates a comparison between estimated and actual values.

Table 9.Results of confirmation test

	Optimum control parameters	
	Predicted	Experimental
Level	$A_4B_1C_1$	$A_4B_1C_1$
S/N ratio for specific wear rate (dB)	10.60	11.8

4. Conclusions

Taguchi's model approach can be utilized to investigate the dry sliding abrasive wear behaviour of a manufactured polymer composite. The following are the broad findings that can be derived from the research.

- It is discovered that the Taguchi method's parameter design provides a simplistic, systematic, and efficient way for optimizing wear test parameters.
- The sample S4 has the lowest average wear loss. Therefore, the sample S4 exhibits the highest wear resistance property.
- The specific wear rate is greatly influenced by the material type, speed, and sliding distance, which are 40.90%, 34.56%, and 24.11%, respectively.
- Multiple linear regression equation has been developed with R-Sq value 97.6%. A validation experiment demonstrates that the error associated with the wear loss of the specimen ranges from 1.96% to 10.93%.
- The predicted S/N ratio for specific wear rate could be determined using the ideal testing specifications, and a satisfactory agreement between predicted and actual specific wear rates was found at a confidence level of 95%.

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