Wear analysis of natural-inorganic fiber reinforced brake composites using Taguchi's technique

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ABSTRACT

Brake friction composite materials comprising varying proportions of natural (banana) and inorganic (lapinus) fibers were designed, fabricated by compression moulding and characterized for sliding wear performance. The sliding wear properties of the manufactured friction composites have been studied by the Taguchi method. An orthogonal array (L_{16}) was used to investigate the influence of sliding wear parameters. A series of tests were conducted on a pin-on-disc machine by considering four control parameters: composition, normal load, sliding velocity, and sliding distance, each having four levels. The results showed that the wear in terms of weight loss decreases with increasing banana fiber and increases with increasing lapinus fiber, normal load, sliding velocity and sliding distance. The results indicate that the normal load emerges as the most significant control parameter affecting wear performance, followed by sliding distance and sliding velocity.

Keywords: *Sliding wear, Friction composite, Natural fiber, Taguchi*

1. Introduction

Composite friction materials are widely used for automotive braking applications. Friction composites contain more than twenty components (classified as space fillers, binders, reinforcing fibers and friction modifiers), which work together to produce a high and stable friction coefficient and low wear over a wide range of operating conditions [1, 2]. Literature related to the role of various reinforcing fibers, space fillers, binders, property modifiers and nanofillers is widely reported [3–7]. Similarly, optimization of friction materials using decision-making models and several soft computing-based techniques are reported to optimize friction composites [8]. Among various components, fibrous reinforcements: such as organic fibers, inorganic fibers, metallic fibers, and their combinations, have been found to play an important role as they reinforce composites during production and also help in the formation of topographical features which help in the increment of tribological properties [9]. These fibers are synthetic and display many drawbacks, including non-recyclability, higher cost and energy consumption. Moreover, the wear particles generated during the braking also contain several hazardous elements that threaten the environment. In addition, the wear particles released during braking reported containing a few hazardous components which previously demonstrated danger to the environment [10]. Nowadays, natural fibers are extensively used in many applications and can be proved a potential candidate for friction composites because of various beneficial characteristics, including biodegradability [11–14]. Lapinus fiber is an inorganic mineral and contains a significant quantity of silica, alumina, calcium oxide, and magnesium oxide [15]. Lapinus fiber has high thermal

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Table 1. Ingredients and designation

Composition [wt.%]	Composite designation			
	BL-1	BL-2	BL-3	BL-4
Base composition*	70	70	70	70
Banana fiber	2.5	5	7.5	10
Lapinus fiber	27.5	25	22.5	20

* Graphite=5 wt.%, Barium sulphate=50 wt.%, Phenolic resin=15 wt.%

stability and has improved the tribological characteristics of brake friction materials under a wide range of operating conditions [15, 16]. Therefore, the effect of natural fiber in combination with inorganic fiber on wear performance of brake friction composite was assessed and reported in this article.

2. Experimental details

2.1. Materials and fabrication

The friction composites used in the present study consists of phenolic resin, banana fiber, lapinus fiber, barium sulphate and graphite amounting to 100% by weight were fabricated. Detailed descriptions for each manufacturing condition are briefly reported elsewhere [11, 12]. Specimen of size 20 mm x 10 mm x 10 mm were cut from the fabricated friction composites for this research work.

2.2. Sliding wear test

The wear performance of the manufactured friction composites was studied using a pin-on-disc machine (DUCOM) as per ASTM G 99 [17]. A series of tests are conducted with selected operating conditions of load, velocity and distance. The material loss from the composite surface before, and after testing was measured and the wear in terms of weight loss (Δw) was reported using Eq. (1):

$$\Delta w = w_i - w_f, \tag{1}$$

where w_i and w_f were the sample weight before after testing.

2.3. Taguchi based experimental design

The experimental design was created in order to see how introducing control elements affected the method's outcomes. Taguchi is a method for designing experiments to obtain data in a controlled mode while optimizing the task using certain variables. It is a straightforward and methodical strategy of optimizing design for quality, cost, and performance and is widely utilized in industrial, management, and research applications [18–20]. This procedure entails a series of tests to determine the appropriate parameters for low wear and friction characteristics. The output is estimated for all collections of the evaluated levels of a factor in the Taguchi technique. This method can be used to investigate input variables by determining the significant components that influence the outcome. In addition, the investigation may offer the best set of these factors [18]. The method used orthogonal array design to reduce the number of experiments [19]. In this study, the L16 orthogonal array was constructed using the Taguchi technique to study the influence of selected operating parameters on the wear performance of the manufactured friction composites. Minitab® 17 was used to create a mathematical model and find the best conditions for minimizing sliding wear. There were 16 experimental runs with four control factors at four levels. The sliding wear tests on the composites

Table 2. Control parameters and levels used in the experiment

Control parameters	Levels			
	I	II	III	IV
A: Composition [wt.%]	BL-1	BL-2	BL-3	BL-4
B: Normal load [N]	25	50	75	100
C: Sliding velocity [m/s]	1.5	3	4.5	6
D: Sliding distance [m]	1 000	2 000	3 000	4 000

are carried out under different operating conditions considering four control parameters, composition, sliding velocity, normal load and sliding distance each at four levels as listed in Table 2. After that, signal-to-noise ratio (SNR) analysis of the obtained experimental results was carried out to determine the optimal combination of control parameters resulting in lower wear. There are three types, namely higher-the-better, lower-the-better and nominal-the-better, applicable for SNR analysis. In the study of friction composites, one of the most important targets is identifying the combination of control parameters under which minimum wear would occur. Therefore, lower-the-better analysis was used in this study and SNR was calculated using Eq. (2) [18–20].

$$SNR = -10\log\frac{1}{\alpha}\sum\beta^2, \tag{2}$$

where α is number of tests, and β is the weight loss. Following SNR analysis, the effictiveness of each control parameter on wear performance was evaluated in terms of contribution ratio using using following steps [20]:

Step #1: The overall SNR mean ($\overline{SNR}$) is computed as:

$$\overline{SNR} = \frac{1}{16}\sum_{\alpha=1}^{16}(SNR). \tag{3}$$

Step #2: In this step level mean of SNR (ω) for each control parameter was computed as:

$$\omega_i = \frac{1}{4}\sum_{j=1}^{4}(SNR)_{ij}, \tag{4}$$

where i is the control parameter and j means the corresponding level.

Step #3: In this step sum of square value ($\overline{\omega}$) for each control parameter was determine using variations of ω_i with respect to $\overline{SNR}$ as:

$$\overline{\omega_i} = \sum_{J=1}^{5}(\omega_i - \overline{SNR})^2. \tag{5}$$

For all control parameter it can be determined as:

$$\overline{\omega} = \sum_{i=1}^{4}(\omega_i - \overline{SNR})^2. \tag{6}$$

Step #4: Finally the contribution ratio (Δ_i) for each control parameter was determine using following equation:

$$\Delta_i = \frac{\overline{\omega_i}}{\overline{\omega}}100. \tag{7}$$

The overall mean ($\overline{SNR}$) for the conducted 16 experiments was determined using Eq. (3) and found to be 43.68 dB. The level mean of SNR (ω) values for each control parameter are computed by using Eq. (4). For composition, the ω value determined as:

$$\omega(\text{composition, BL-1}) = \frac{1}{4}[51.70 + 42.82 + 32.43 + 26.86] = 38.45, \tag{8}$$

$$\omega(\text{composition, BL-2}) = \frac{1}{4}[49.44 + 48.60 + 50.12 + 32.63] = 45.20, \tag{9}$$

$$\omega(\text{composition, BL-3}) = \frac{1}{4}[44.72 + 37.10 + 49.05 + 45.45] = 44.08, \tag{10}$$

$$\omega(\text{composition, BL-1}) = \frac{1}{4}[47.89 + 51.90 + 47.68 + 40.54] = 47.00. \tag{11}$$

Similarly for sliding distance value computed as:

$$\omega(\text{sliding distance, 1 000 m}) = \frac{1}{4}[51.70 + 50.12 + 45.45 + 51.90] = 49.79, \tag{12}$$

$$\omega(\text{sliding distance, 2 000 m}) = \frac{1}{4}[42.82 + 32.63 + 49.05 + 47.89] = 43.10, \tag{13}$$

$$\omega(\text{sliding distance, 3 000 m}) = \frac{1}{4}[32.43 + 49.44 + 37.10 + 40.54] = 39.88, \tag{14}$$

$$\omega(\text{sliding distance, 4 000 m}) = \frac{1}{4}[26.86 + 48.60 + 44.72 + 47.68] = 41.97. \tag{15}$$

For individual control parameter the value determined using Eq. (5) as follows:

$$\varpi_{\text{composition}} = [(38.45 - 43.68)^2 + (45.20 - 43.68)^2 + (44.08 - 43.68)^2 + (47.00 - 43.68)^2] = 40.85. \tag{16}$$

Similarly for sliding distance it can be determined as:

$$\varpi_{\text{sl.dist.}} = [(49.79 - 43.68)^2 + (43.10 - 43.68)^2 + (39.88 - 43.68)^2 + (41 - 97 - 43 - 68)^2] = 55.03. \tag{17}$$

For all control parameters ϖ_i value can be determined using Eq. (6) as:

$$\varpi = [\varpi_{\text{composition}} + \varpi_{\text{normal load}} + \varpi_{\text{sliding velocity}} + \varpi_{\text{sliding distance}}], \tag{18}$$

$$\varpi = [40.85 + 79.44 + 42.37 + 55.03] = 217.69. \tag{19}$$

Finally the Δ_i value for contribution ratio of each control parameter was computed using Eq. (7) as:

$$\Delta(\text{composition}) = \frac{40.85}{217.69} \cdot 100 = 18.77\%. \tag{20}$$

Similarly for sliding distance Δ_i value computed as:

$$\Delta(\text{sliding distance}) = \frac{55 - 03}{217.69} \cdot 100 = 25.28\%. \tag{21}$$

The mean of means value was the average wear value for each level of each control parameter. For example, in Table 3, the mean of means value for level I (BL-1) of control parameter A is obtained

Table 3. Experimental design and wear results with corresponding SNR

Test run	A	B	C	D	Wear [g]	SNR [dB]
1	BL-1	25	1.5	1 000	0.00260	51.70
2	BL-1	50	3.0	2 000	0.00722	42.82
3	BL-1	75	4.5	3 000	0.02390	32.43
4	BL-1	100	6.0	4 000	0.04540	26.86
5	BL-2	25	3.0	3 000	0.00337	49.44
6	BL-2	50	1.5	4 000	0.00371	48.60
7	BL-2	75	6.0	1 000	0.00312	50.12
8	BL-2	100	4.5	2 000	0.02335	32.63
9	BL-3	25	4.5	4 000	0.00581	44.72
10	BL-3	50	6.0	3 000	0.01397	37.10
11	BL-3	75	1.5	2 000	0.00353	49.05
12	BL-3	100	3.0	1 000	0.00534	45.45
13	BL-4	25	6.0	2 000	0.00403	47.89
14	BL-4	50	4.5	1 000	0.00254	51.90
15	BL-4	75	3.0	4 000	0.00413	47.68
16	BL-4	100	1.5	3 000	0.00938	40.55

by calculating the average of wear responses of test run 1, 2, 3 and 4, which all involve BL-1 level of composition (see Table 3):

$$\text{Mean of means for BL-1} = \frac{0.0026 + 0.00722 + 0.0239 + 0.0454}{4} = 0.01978, \tag{22}$$

$$\text{Mean of means for BL-4} = \frac{0.00403 + 0.00254 + 0.00413 + 0.00938}{4} = 0.00502. \tag{23}$$

Similarly, the mean of means value for level IV (4 000 m) of sliding distance is obtained by calculating the average of wear responses of test run 4, 6, 9 and 15 as:

$$\text{Mean of means for 4 000 m} = \frac{0.0454 + 0.00371 + 0.00581 + 0.00413}{4} = 0.01476. \tag{24}$$

3. Results

The experimental results were analyzed using the Taguchi method, and the combination of control parameters and the most significant parameter affecting manufactured composite wear are identified. Table 3 shows that the change in composition, normal load, sliding velocity, and sliding distance much influenced the wear. Generally, the lowest weight loss of 0.00254 g was observed for composite BL-4 at 50 N normal load, 4.5 m/s sliding velocity and 1 000 m distance. The highest weight loss was observed for composite BL-1 at 100 N load, 6 m/s sliding speed with 4 000 m distance, and the order of 0.0454 g. It has been known that the highest SNR level is the optimal level for the control parameter. From Fig. 1, the optimal combination of the control parameter for wear is determined as A4 (BL-4 composition), B1 (25 N normal load), C1 (1.5 m/s sliding velocity) and D1 (1 000 m sliding distance). The corresponding plot for mean of means for wear is presented in Fig. 2. From the Fig. 1 and Fig. 2, it can be observed that the SNR response of wear increases (Fig. 1) with

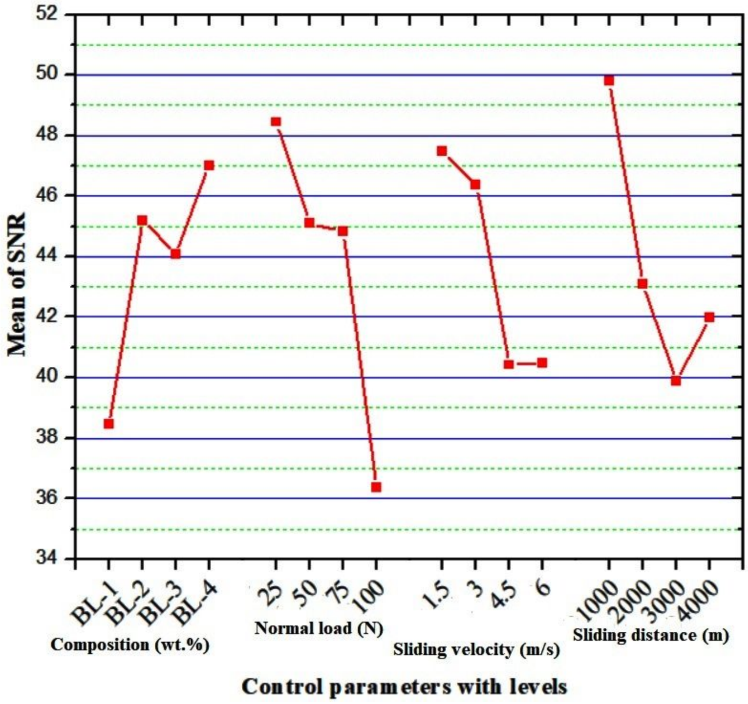

Figure 1. Main effect plot for mean of SNR

the inclusion of increased banan fiber content with corresponding decrease in lapinus fiber content, implying that the means (Fig. 2) of wear decrease. From Fig. 1, it can observed that SNR response decreases with increase in normal load, sliding distance and sliding velocity values. This decrease in SNR indicating that the wear of the composites increases gradually with an increase in normal load, sliding velocity and sliding distance. The wear observed decreased with increasing soft, i.e. banana fiber, and increased with hard lapinus fiber. For BL-1 composite, the amount of soft fiber is low

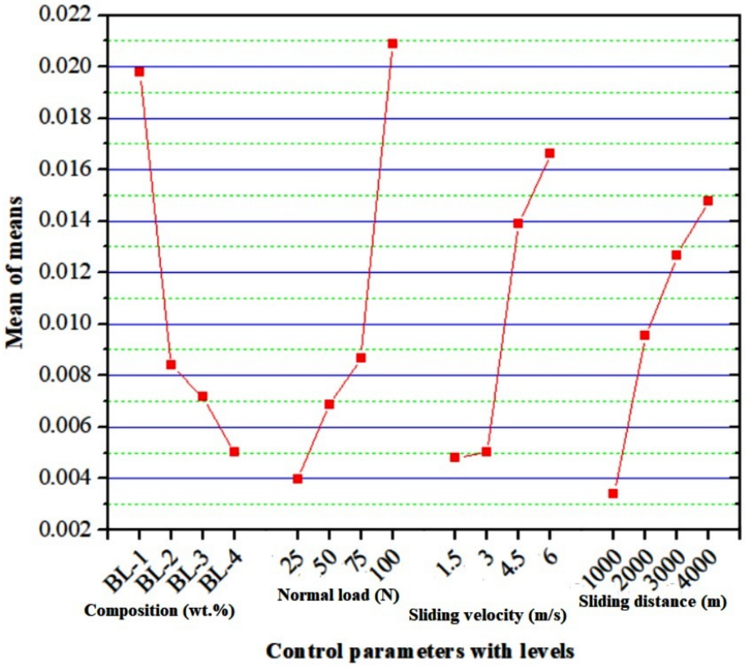

Figure 2. Main effect plot for mean of means

Table 4. Contribution ratio results

Control Parameter	$\overline{SNR}$	$\overline{\omega_i}$	$\overline{\omega}$	Δ_i
Composition [wt.%]	43.68	40.85	217.69	18.77
Normal load [N]		79.44		36.49
Sliding velocity [m/s]		42.37		19.46
Sliding distance [m]		55.03		25.28

(2.5 wt.%), while the higher amount of hard ingredients (nearly 27.5 wt.%) easily detached from the composite surface due to frictional heat generated during sliding resulted in increased wear. While in the case of BL-4 composite having nearly 20 wt.% of lapinus fiber, a higher amount of soft banana fiber (10 wt.%) was exposed on the surface that helps in reducing the wear of the composites [15]. The obtained trend for SNR and the mean of means graph are correlated to how they are calculated. The mean of means value was the average wear value for each level of each control parameter. Whereas the SNR is calculated using Fig. 2. In the Taguchi approach, a measure of robustness is used to identify control parameters that reduce variability in a process by minimizing the effects of uncontrollable factors such as noise that cannot be controlled during product design. The fluctuations in the SNR represent the experimental variation/error due to uncontrolled noise. Using the Taguchi approach, one can handle noise factors and determine the optimal parameter settings that minimize the effects of the noise [21].

Further the effectiveness of control parameters was analyzed in terms of contribution ratio as described in Table 4 and presented in Eq. (8-21). The order of the parametric usefulness for wear was normal load > sliding distance > sliding velocity > composition. The result reveals that normal load has the most dominant influence on wear with a percentage contribution of 36.49%, followed by sliding distance and sliding velocity with 25.28% and 19.46%, respectively. While composition has the lowest influence with a percent contribution of 18.77%.

4. Conclusions

Dry sliding wear response of banana and lapinus fiber reinforced brake friction composite materials under varying conditions of load, sliding velocity and sliding distance was successfully analyzed using Taguchi's experimental design method on a pin-on-disc machine. Results revealed that the composition of 10 wt.% banana fiber, 20 wt.% of lapinus fiber at 25 N load, 1.5 m/s sliding velocity and 1 000 m of sliding distance exhibit the lowest wear. It was also concluded that normal load primarily influences wear with a contribution of 36.49%, followed by sliding distance and sliding velocity with 25.28% and 19.46%, respectively. While composition have a minor influence on wear with a contribution of 18.77%.

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