P-ISSN 2586-9000
E-ISSN 2586-9027
Homepage : *https://tci-thaijo.org/index.php/SciTechAsia* Science & Technology Asia
Vol.29 No.3 July - September 2024 Page: [146-157]

Original research article

Wear Behavior Optimization of E-Glass Reinforced Polymer Matrix Composites for Automotive Applications

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Received 9 February 2024; Received in revised form 12 July 2024
Accepted 8 August 2024; Available online 25 September 2024

ABSTRACT

The proposed study focuses on developing multiphase hybrid composites comprising Epoxy matrix and E-Glass fibers, and investigating their wear behavior under varying process conditions. The research employs the Taguchi method to optimize parameters (load, speed, sliding distance) that affect wear. Experimental tests on a specialized rig simulate wear under different conditions, and analysis tools like orthogonal arrays and analysis of variance are used to determine optimal input levels and their impact. Observed findings show that load, speed, and sliding distance significantly affect wear rate and optimal settings (20 N load, 400 rpm speed, 100 m sliding distance) minimize wear rate. For instance, at 10 N load, 200 rpm speed, and 50 m sliding distance, initial wear is 201.12 microns, projected wear rate after Taguchi optimization is about 206.9 microns. Confirmation test measures around 211.52 microns. The study highlights Taguchi's efficiency in optimizing process parameters, aiding design for hybrid composites. This approach enhances production processes, meeting industry demand for such materials also findings offer insights into settings to achieve optimal wear rate, enhancing hybrid composite performance and manufacturing sector's ability to meet material demands.

Keywords: E-Glass; Polymer composite; Product innovation; Sustainable manufacturing; Taguchi optimization; Wear resistance

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1. Introduction

Wear is the most significant parameter of the mechanical component, specifically when two contacting surfaces have relative motion likely rotary or sliding motion. For the current work, a clutch is considered as an application. Existing clutch materials have limitations like expensiveness, low strength to weight ratio, heavy weight, low wear resistance and complications in replacements. High strength, lightweight, corrosion resistance, thermal stability, and wear resistance make E-glass reinforced epoxy composites ideal for clutch applications. Clutch facings, discs, and pressure plates issue from their performance, durability, and efficiency. Composite clutch system components are lighter, more fuel efficient, and have better vibration dampening than metal components, resulting in smoother operation and extended service life. The proposed work is an attempt to reveal and rectify the effect of the various parameters optimal level on the proposed hybrid composite and its usefulness to overcome the problems associated with existing materials.

An optimization process tries to produce better results by changing the input parameters in order to improve system performance. Global and local optimization strategies can often be divided into two categories. The gradient-based methodology is considered a local optimization approach, whereas Taguchi's method, simulated annealing, genetic algorithms, particle swarm optimization, and genetic algorithms are viewed as global optimization techniques [1]. Regarding mechanical qualities, the process variables for creating composites made of polypropylene and wool were optimized by Govinda Raju [2]. For this investigation, a fabrication method based on compression molding was taken into consideration. The manufacturing process can be optimized for hemp and polypropylene composites [3]. It was claimed that the best way to achieve the ideal qualities of the composites was to optimize the fabrication process, particularly the compounding process. Numerous studies have been performed on controlled variable improvements to enhance the performance of composite materials [4–7].

Surface roughness process factors for turning glass fiber-reinforced composites need to be addressed according to Hussain [4] who employed a genetic algorithm. Maheswaran and Renald [5] used an artificial neural network to analyze the wear behavior of hybrid composites made of Al6061, Al2O3, and graphite. Using RSM and ANN algorithms, the mechanical behavior of particle-filled coir polyester composites was anticipated and strengthened by Sathiya Murthy et al. [6]. Using an iterative map reduction guided particle swarm optimization approach, Xu and You [7] attempted to improve multiple process variables. The design of experiments (DOE) based on the Taguchi methodology is one of many optimization strategies. Designers can use DOE approaches to examine the simultaneous effects of various variables that may have an impact on a design's output consequences. For a given set of components, all configurations will be displayed in a complete factorial format. A complete factorial design produces several experiments because the majority of research experiments often involve a significant number of elements. Only a tiny set of options from all the available options is chosen in order to keep the number of tests at a manageable level. A partial fraction experiment is a technique for choosing a constrained set of trials that generates statistics. Although this method is widely recognized, there are no universal rules for applying it or evaluating the findings of the trials. Taguchi has proposed a brand-new method for conducting experiments that are dependent on set guidelines. This technique allows the use of a unique collection of arrays called orthogonal arrays. These common arrays specify how to carry out the fewest possible tests that could provide comprehensive knowledge of all the variables that influence the performance parameter. Numerous academic fields, such as agribusiness fields of science, geoscience, and health, use the E-Glass reinforced composites [8].

The best cutting parameter was found by Uysal et al. [9] using the Taguchi approach and analysis of variance, who also looked into how different factors affected tool wear. Taguchi analysis was frequently utilized by researchers to determine the best variable setting for the erosive behavior of materials [10–12]. Rout [10] conducted a study to investigate the erosive wear response of hybrid glass polyester and graphite composites. He utilized the Taguchi approach to optimize the parameters and understand the behavior of alumina-filled glass/polyester hybrid composites during corrosive wear. Similarly, Patnaik [11, 12] employed the Taguchi experimental design in his research, focusing on the parametric optimization of hybrid composites. The study used striking velocity, SiC wt. %, safety clearance, angle of incidence, and disintegration measurement as its benchmark variables. The DOE method was also used by researchers to pinpoint the variables that affect how the polymer composites wear when they slide. Dry sliding wear studies, carried out by Rout and Sathapathy [13], used the Taguchi experimental design. According to observations, the specific wear rate was significantly impacted by variables like momentum, ingredient volume, and load.

By utilizing the Taguchi approach, Padhi and Sathapathy [14] examined the sliding wear behavior of composites containing blast furnace slag and determined the ideal parameter selections to lower the erosion percentage. It was discovered that the sliding velocity had a greater impact on the rate of wear. Basavarajappa et al. [15] successfully used the Taguchi technique to examine the sliding wear behavior of composites using control factors. According to an experimental study by Anjum et al. [16], the sliding distance, followed by the applied weight and sliding velocity, is the most crucial element. Raju et al. [17] investigated the wear behavior of silicon carbide-filled glass fabric-reinforced epoxy composites using the Taguchi experimental design method. Kevlar fiber-reinforced epoxy composites' three-body abrasive wear behavior was examined by Agrawal et al. [18] using the Taguchi design method. Abrasive size, sliding velocity, sliding distance, normal load, and fiber loading were found to be the study's control criteria. Optimization of wear test parameters was investigated using the Taguchi method for the design of experiments for hybrid composites [19].

Hybrid woven fiber composite material using epoxy as the resin has been used in the current research work. Optimizing E-glass reinforced epoxy composites for clutch applications is new since it addresses the constraints of existing materials. This study uses sophisticated optimization methods including the Taguchi method to improve hybrid woven fiber composite clutch component wear resistance, strength, and efficiency. This method improves manufacturing and targets characteristics to optimize performance and durability. The study's novel application of global and local optimization methodologies promises more effective and efficient clutch systems with longer service life and higher fuel economy.

2. Methodology

In this proposed research E-Glass/Epoxy reinforced composites were developed using a compression molding technique, which is well known for its pore free and high-quality products [20–22]. The wear rate is addressed in the current study's focus on improving the effectiveness of process variables in hybrid materials. There are several steps involved, such as choosing the best clutch frictional material and determining the influential factors etc. [23, 24]. The experiment is conducted on an orthogonal array, and the results are analyzed using statistical methods such as Taguchi's method, analysis of variances (ANOVA), and regression analysis. Selecting the best design parameters for performance and cost can be done in a systematic and efficient manner using the Taguchi approach. With few experiments, it explores a variety of variables using orthogonal arrays. The Signal-to-Noise (S/N) ratio and graphs are used to analyze the results, and linear graphs help to attribute effects to the columns of the orthogonal array. Effect of noise components on the quality characteristic is evaluated using the S/N ratio, a performance metric. Product design should meet the target response with the least amount of variability possible. The Taguchi technique provides an effective and methodical approach to experimental design and analysis, assisting in the identification of optimal parameter settings for increased quality and performance. It does this by utilizing orthogonal arrays, linear graphs, and S/N ratios [25, 26].

2.1 Signal-to-Noise (S/N) ratio

The S/N ratio is a performance indicator used to quantify the influence of noise effects on a quality attribute. In the context of this study, three S/N ratios have been defined to optimize the objectives. The purpose of these ratios is to provide a product design that simultaneously achieves the target response while minimizing variance.

$$\frac{s}{N_t} = 10\log(\frac{y^2}{s^2} - \frac{1}{n}), \tag{2.1}$$

$$\frac{s}{N_s} = -10\log(\frac{1}{n}\sum y^2), \tag{2.2}$$

$$\frac{s}{N_1} = -10\log(\frac{1}{n}\sum \frac{1}{y^2}), \tag{2.3}$$

where Eq. (2.1) is for a nominal-the-best-situation, Eq. (2.2) in the case of the smaller-is-better criterion, and Eq. (2.3) mostly in final larger-is-better scenario. In this study, the symbol $\sum$ is used to indicate summation over the values of the outer array, while the var s represents the standard deviation calculated from the values of the outer array. This standard deviation quantifies the variability introduced by noise factors. The calculation of the Signal-to-Noise ($\frac{S}{N}$N) ratio is performed for each value of the inner array across the entire outer array. The objective is to maximize each $\frac{S}{N}$ ratio for practical purposes. A comprehensive Taguchi analysis entails examining the $\frac{S}{N}$ ratio, considering the number of measurements in a trial/row, and assessing the influence of different variables on the effectiveness of a particular technique or product execution. By analyzing the $\frac{S}{N}$ ratios and understanding their relationship with the variables, valuable insights can be gained to optimize the process and improve the overall performance of the system. The goal is to identify the optimal settings for these factors, enabling the product to function properly under various circumstances and throughout its intended use. To meet this need, the product must exhibit resistance to various variables and elements, collectively referred to as noise factors that can interfere with its performance [29–31]. Taguchi has identified three groups of noise factors: outside noise, internal noise, and manufacturing variances. Products that can withstand these three types of noise factors are considered to be of high quality, as they demonstrate robustness and reliability. [22–25, 32].

2.2 Experimental procedure

The current research study considers the applied load (N), sliding speed (m/s), and sliding distance (m) as the optimal parameters. The selection of these levels is based on a comprehensive assessment of the literature, as depicted in Table 1.

Table 1. The optimal parameters.

Sr. No.	Parameter	Phase 1	Phase2	Phase3
1	Applied Load (N)	A 10	15	20
2	Sliding Speed (rpm)	B 200	300	400
3	Sliding Distance (m)	C 50	75	100

As suggested in the objective high-strength compositions, wear experiments have been performed in this section using a variety of operational parameters to identify the best process parameters for the expected configuration's proposed wear performance. The sliding wear performance study was conducted following the ASTM G-99 standard. To optimize the process parameters and enhance accuracy, the smaller-is-better option was chosen as the criterion. In order to minimize the number of tests to nine, a mix L9 orthogonal array was selected. Table 2 presents the wear rate values along with the corresponding signal-to-noise ratios obtained from the completion of these trials using the designated levels of input parameters.

Table 2. Wear rate with S/N ratio.

Sr. No	A (N)	B (rpm)	C (m)	Wear Rate (Micron)	S/N Ratio
1	10	200	50	201.12	46.0691
2	10	300	75	483.256	53.6835
3	10	400	100	1016.49	60.1421
4	15	200	75	305.485	49.6998
5	15	300	100	577.312	55.2282
6	15	400	50	1215.813	61.6973
7	20	200	100	410.625	52.2689
8	20	300	50	621.568	55.8698
9	20	400	75	1209.312	61.6508

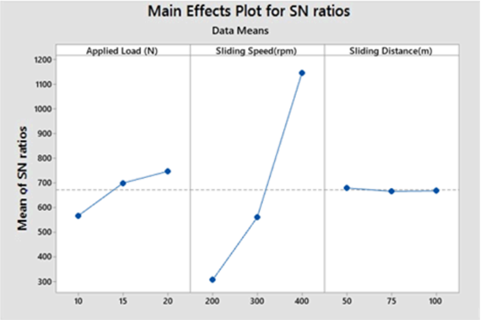

Fig. 1. Graphical representation of effect of parameter for S/N ratio.

3. Results and Discussion

The response ratios for wear rate, determined by the S/N ratio analysis, are presented in Table 3. The smaller option, which was found to be superior in terms of wear rate, was selected for further investigation. By examining the S/N ratio, the optimal level of wear rate can be identified. Additionally, the ranking of the parameters can be observed, indicating their relative influence on the wear rate. This analysis helps to understand the key factors that contribute to the wear rate and provides valuable insights for optimizing the process parameters in order to achieve the desired performance.

3.1 Graphical representation of effect of parameter on S/N ratio

The information regarding the selection of the best values and the impact of each parameter on the wear rate is depicted in Table 3. Based on this analysis, it is recommended to choose the level that corresponds to the maximum S/N ratio value for achieving the optimal configuration. According to Table 2, the applied load, sliding speed, and sliding distance should be maintained at levels 3, 2, and 1, respectively, in order to minimize the wear rate. These levels have been determined to provide the most favorable conditions for reducing wear and optimizing the performance of the hybrid composites. By following the recommendations indicated in Table 3 and maintaining the parameters at the suggested levels, it is expected to achieve the desired outcomes in terms of wear rate reduction and enhanced performance of the composites.

Table 3. SN response ratios .

Level	A (N)	B (rpm)	C (m)
1	-53.30#	-49.35#	-54.55
2	-55.54	-54.93	-55.01
3	-56.6	-61.16	-55.88#
Delta	3.3	11.82	1.33
Rank	2	1	3

Note: # - optimum level

3.2 Response of means for wear rate

Table 4 presents the ideal settings for achieving a lower variance in the study. The applied load, sliding speed, and sliding distance were ranked as the third, first, and second factors, respectively, based on their impact on the wear rate and overall performance of the hybrid composites. To minimize the variance and optimize the process parameters, it is recommended to prioritize the sliding speed as the most influential factor by setting it at the first level. This indicates that maintaining a specific sliding speed value, as indicated in Table 4, would contribute significantly to reducing the variance in wear rate.

3.3 Bi-variate correlation test

Table 4. Response of Means.

Level	A(N)	B (rpm)	C(m)
1	567	305.7	679.5#
2	699.5	560.7	666
3	747.2#	1147.2#	668.1
Delta	180.2	541.5	13.5
Rank	2	1	3

Note: # - optimum level

The applied load, identified as the third factor, should also be controlled at the suggested level to ensure a lower variance. This implies that by maintaining the applied load within the specified range, as outlined in Table 4, the variability in wear rate can be effectively minimized. Similarly, the sliding distance, ranked as the second factor, should be carefully controlled at the recommended level. By adhering to the specified sliding distance values presented in Table 4, the variance in wear rate can be further reduced. Overall, by considering the ideal settings provided in Table 4 and focusing on the prioritized factors (sliding speed, applied load, and sliding distance), it is anticipated that a lower variance in wear rate can be achieved, leading to improved consistency and performance of the hybrid composites.

3.4 Graphical representation of effect of parameter on Means

For optimal configuration, it is advised to select the level that corresponds to the maximum S/N ratio value. Analyzing Fig. 2, it is clear that the applied load should be set to level 3, the sliding speed to level 1, and the sliding distance to level 2 for the highest S/N ratio. By preserving these precise parameter values, the desired optimal configuration can be attained, resulting in enhanced performance and decreased variability.

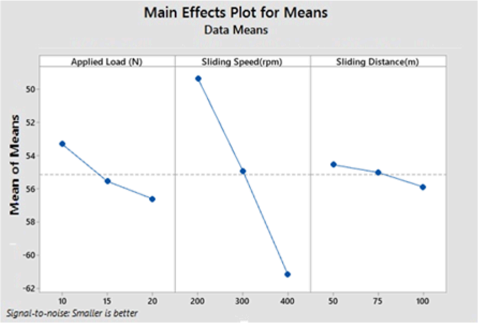

Fig. 2. Effects of Means.

This graphical representation illustrates the effect of each parameter on the S/N ratio in a straightforward manner. Similarly contour plots for the various process parameters with respect to the wear rate is depicted in Figs. 3-5 respectively. A contour plot clearly indicates the impact of process parameters on the wear rate of the developed samples. It emphasizes the importance of choosing the optimal parameter levels to optimize the wear properties of hybrid composites. To achieve the optimal configuration with the highest S/N ratio values, it is recommended, based on Fig. 4, to maintain the applied load at level 3, the sliding speed at level 1, and the sliding distance at level 2. Adherence to these recommendations will enhance the overall performance and reduce the variability of the hybrid composites' wear characteristics.

3.5 Regression analysis

Regression analysis is a statistical tool employed to investigate the association between variables. It aims to establish a cause-and-effect relationship in simple regression by examining two variables. In multiple regressions, additional factors can be introduced individually to assess their influence. The obtained regression equation facilitates analysis, wherein the regression coefficient and R-square value are utilized. Regression coefficients show the average effect on the response variable for a unitary change in the predictor variable while

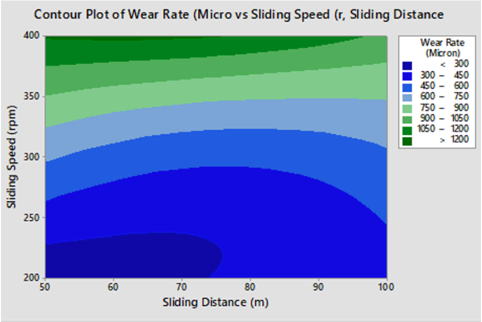

Fig. 3. Contour plot - Wear rate vs. Sliding speed vs. Sliding Distance.

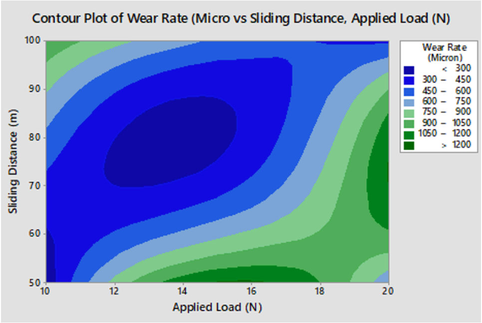

Fig. 4. Contour plot - Wear rate vs. Sliding Distance vs. Applied Load.

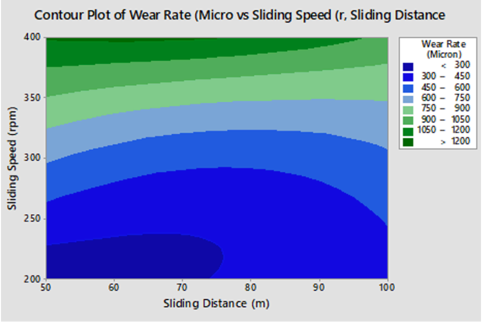

Fig. 5. Contour plot - Wear rate vs. Sliding speed vs. Sliding distance.

holding other predictors constant. The R-square value measures how closely the data matches the fitted regression line. The wear estimations can be represented by the following predictive equations. These equations provide valuable insights into estimating wear based on the identified predictor variables, further enhancing our understanding of the wear behavior in the studied system.

$$WR = -1814 + 4.207 \times S + 0.23 \times d + 18.02 \times N, \tag{3.1}$$

where the WR =Wear Rate in Microns; S =Sliding Speed in rpm; d =Sliding distance in meter; N =applied load in Newton.

The statistical technique known as ANOVA (Analysis of Variance), which identifies variations in the performance of tested item groups, enables an objective approach to decision-making. It enables a formal assessment of the significance of key components and their interrelationships by contrasting the mean square with an estimate of experimental errors at specific levels of confidence. In this study, the Signal-to-Noise (S/N) ratios' overall variability is investigated using an ANOVA. The total variability of the S/N ratios is calculated as the sum of squared deviations from the overall mean S/N ratio. Both the error term and the contributions from each design parameter are considered in this calculation. The total sum of squared deviations (SST) from the overall mean S/N ratio can be calculated using the formula below [26]. This calculation provides helpful information about the overall variability of the S/N ratios and aids in determining the significance of the design parameters in relation to the observed variations.

$$SST = \sum_{i=1}^{n} (n_i - n_m)^2, \tag{3.2}$$

where, i mean Single to noise ratio for the ith experiment and n is number of experiments in the orthogonal array.

The formula below can be used to determine the % addition P:

$$P = \frac{SSd}{SSt}, \tag{3.3}$$

where the sum of the squared deviations (SSd) and the total sum of the squared deviations (SSt) are expressed. The F-ratio in the study, which compares the mean square error to the residual error, is typically used to assess a factor's importance. If $F > F = 5\%$, the F-ratio that corresponds to the process parameters and specific process parameters at a 95% confidence level will be statistically significant.

3.6 ANOVA analysis

The P value, which is reported in Table 5, indicates the significance level (appropriate and unsuitable). The impact of process factors on wear rate is expressed as a percentage (%).

The percentages show that the accuracy of the hole diameter is significantly influenced by the applied weight, Sliding Speed, and sliding distance. Table 5 shows that in the dry condition, sources A, B, and C had respective effects on the rate of material removal of 18.513%, 75.83%, and 3.76%, respectively. Because the test $F > F = 5\%$, as indicated in Table 5, the sliding speed factor has both statistical and physical relevance to the wear rate value.

3.7 Confirmation experiment

The confirmation experiment is essential to the parameter design process, particularly when screening or small fractional factorial experiments are employed. The study's confirmation experiment's goal was to confirm that the optimal wear rate parameters discovered by the experimental investigation matched the value predicted. The

Table 5. ANOVA for wear rate.

Source	DF	SS	MS	F-value	p-value	C (%)
A (N)	1	194	194	0.11	0.757	18.51
B (rpm)	2	52323	26162	15.52	0.026	75.83
C (m)	2	1117041	558520	331.23	0	3.76
Error	3	5059	1686			1.9
Total	8	1174616				100

SS-Sum of Squares, DF-Degree of freedom, C -Percentage contribution, F-Fisher test and MS-MeanSquare

experimental confirmation test is the last step in validating the results obtained using Taguchi's design process. Taguchi strongly suggests the verification of the experiment's findings as a crucial next step. In this, the ideal parameters are established for the pertinent factors after a predetermined number of trials are completed under a predetermined set of conditions. The average results of the confirmation experiment are then compared to the average that was predicted using the parameters and levels assessed. In this work, the levels of the ideal process parameters ($A_3B_3C_1$) for the wear rate value under dry conditions were used to carry out a confirmation experiment.

Table 6. Confirmation Experiment results.

Pa Particulars	Initial wear-para-meters	Optimal Parameter		
		Predic-tion	Experi-mental	Error (%)
Level	$A_1B_1C_1$	$A_3B_3C_1$	$A_3B_3C_1$	2.52
Wearrate (Microns)	201.12	206.9	211.52	

A confirmation experiment was conducted with the predicted setting in order to analyze the output value after the optimal parameter levels for obtaining a lesser wear rate had been reached. The value of wear rate is shown in Table 6, together with the projected setting and verified experiment. Wear rate values were predicted to be 206.9 microns with the predicted setting value ($A_3B_3C_1$). After conducting a real experiment in the projected setting, wear rate values of 211.52 microns have been recorded. An error of 3.41% has been noticed. This negligible difference between real and expected values leads to the conclusion that the predicted parameters are accurate.

4. Conclusions and Recommendation

This study has used the Taguchi method to investigate how different process variables affected the wear rate during dry sliding. While choosing the parameters, the requirements of the industry and manufacturers have been considered. The creation of innovative processes can aid the manufacturing sector in improving production and better meeting the escalating demand for this kind of material (Hybrid Composite material). The study clearly shows that the Taguchi approach offers a structured and effective approach for the design optimization of the process parameters with less effort that required for most optimization techniques. An L-9 orthogonal array has been used in this study's statistically developed experiments based on Taguchi methodology to measure wear rate.

Additionally, it has been demonstrated through the analysis of confirmation tests that the Taguchi parameter design may successfully validate the ideal process parameters. Using the conceptual S/N ratio approach, regression analysis, ANOVA, and Taguchi's optimization method, the results of this study can be used to figure out the best setting values for getting the best wear rate. The input parameters, such as applied load, sliding speed, and sliding distance, can be maintained at 3 (20 N), 3 (400 rpm), and 1 (100 m) levels, respectively, for lower wear loss. The initial wear revealed is 201.12 microns, considering the parameters applied load, sliding speed, and sliding distance as 10 N, 200 rpm, and 50 m, respectively. Using an optimization tool like Taguchi, the wear rate is predicted to be around 206.9 microns, and after a confirmatory test, the wear rate obtained is around 211.52 microns. The error between the predicted and obtained wear rate values is around 2.52%. This is negligible and acceptable. The designed model is reliable and suitable for use in manufacturing sectors for various similar applications. The created model significantly cuts the time and expense associated with it at the same time increases productivity also. The work may be extended by considering different design parameters and their levels to reveal the performance parameters.

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