Sigma Journal of Engineering and Natural Sciences
Web page info: https://sigma.yildiz.edu.tr
DOI: 10.14744/sigma.2023.00119

Research Article

Optimization of wear parameters & coefficient of friction of SiC and graphite reinforced hybrid aluminium composites

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ARTICLE INFO

Article history
Received: 28 September 2021
Revised: 27 October 2021
Accepted: 21 January 2022

Keywords:
Taguchi Method; Optimization; Dry Sliding Wear; Parameters; Load

ABSTRACT

The wear behaviour of Al6351 reinforced with 2-8 percent Silicon Carbide (SiC) and 2-8 percent Graphite (Gr) hybrid composite during dry sliding conditions was evaluated using the Taguchi technique with regression analysis. Taguchi with regression analysis can be used to seek the best parameters for hybrid aluminium composites. Wear experiments were conducted using a L_9 orthogonal array with the following parameters such as sliding velocity, sliding distance and applied load. The ANOVA (analysis of variance) methodology can be used to determine the impact of each factor. The findings of the investigation revealed that the sliding velocity and load are the two most important factors that determine wear. The extensive experiments are closer to the ANOVA expected values. The Taguchi approach was quite successful in optimising wear parameters, according to confirmation test findings. The influence of each parameter can be identified by ANOVA (Analysis of variance) technique. For Wear the parameter Applied load (L) makes the major support the entire sum of squares 49.57% while sliding speed (S) 37.48% and sliding distance (D) contributes only 0.4% and the factor Applied load (L) 92.29% makes the biggest contribution in frictional force according to ANOVA.

Cite this article as: Rao PM, Vijaya M, Srinivas K, Chilakala DR, Chaitanya KL, Chowdary JR, Vadan BJ. Optimization of wear parameters & coefficient of friction of SiC and graphite reinforced hybrid aluminium composites. Sigma J Eng Nat Sci 2023;41(5):1019−1028.

INTRODUCTION

Alloys play a significant role in a variety of manufacturing applications, and they are a versatile but underutilized material. Wear is a significant issue with alloys, although reducing it is cost effective. Metal matrix composites, on average, outperform basic alloys in terms of wear resistance. The kind, size, and weight percentage of reinforcing particles determine the properties of MMCs. Because of their particle reinforcement, MMCs have a higher wear resistance than whiskers and fibres [1,2].

Wear is a key issue in a variety of engineering applications, such as bearings, machine parts, and gears.

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This paper was recommended for publication in revised form by Regional Editor Sevil Yücel

Published by Yıldız Technical University Press, İstanbul, Turkey

Aluminium composites are used to prevent this problem because of their higher wear resistance at various loads, velocities, and sliding distances [3,4]. So the selected wear parameters are applied load, sliding speed and sliding distance. There is more than one influencing parameter, factorial design is more helpful to test all combinations of test parameter. In further words, the factorial design is a combination of multiple levels in experiments in which there are at least two or more test parameters and at least two or more levels of these parameters. In statistical methods, the full factorial design provides great convenience to researchers in analysis process. Regression analysis and Analysis of variance (ANOVA) are used in the analysis of full factorial experiments.

The Taguchi method is a well-known optimization approach that is utilised in a variety of applications. It›s a tenacious tool for creating high-quality systems. Taguchi design test is a powerful method used to solve different optimization problems by increasing the processing performance with a minimum number of tests. Because of vertical indices developed by taguchi, the number of experiments, loss of time and money are significantly reduced. Taguchi method not only ensures that the solution is achieved with the least number of experiments but also supports the development of high-quality processes and products in every respect. The distinct aspects to determine which has the most impact and which has the least [3,5]. Only literature review can be used to determine which parameters have high influence for any testing process. For a given context, not all of the parameters may be ideal. As a result, multiple linear regression analysis and various mathematical models are employed to obtain ideal values [6]. Many applications require multi-response problems that cannot be solved with the Taguchi method alone. As a result, Taguchi, in combination with multiple linear regression analysis, may be able to help solve these issues.

The anticipated optimum setting does not have to correspond to one of the rows of the matrix experiment when using the Taguchi method for parameter design. As a result, the anticipated optimum levels for the control parameters under investigation are used in an experimental confirmation. The goal is to make sure that the optimum settings provided by the matrix experiments actually produce the expected results. Taguchi method with regression analysis can be used to find the best possible parameters for hybrid aluminium composites. Sliding velocity, sliding distance and applied load were used to perform wear studies using a L_9 orthogonal array. Each parameter›s impact can be identified.

MATERIALS AND METHODS

In the current scenario castings were prepared by liquid metallurgy route and the mechanical properties of both metal matrix (AA6351/SiC) and Aluminium hybrid composite (AA6351/SiC/Gr) were estimated. The castings were prepared with liquid metallurgy process through the reinforcement of 2-8 weight percent of SiC (AA6351/SiC) where as in hybrid composite reinforcement ranging with equal composition from 2 – 8% of SiC and Gr. Improved mechanical properties are observed in AA6351/SiC/Gr hybrid composite through stir casting process as shown in Figure.1. For the prepared samples wear test was conducted.

Figure 1. Stir Casting Equipment.

Wear Test

Wear tests were performed on cylindrical samples using a pin-on-disc wear machine (M/s DUCOM) with a counter face of a solidified and polished disc made of EN-32 steel (HRC 62-65 hardness), track diameter of 100 mm, as illustrated in Figure 2. The composites and matrix alloy were retrieved from the wire cut EDM process to create standard wear pin specimens with a diameter of 6 mm and a height of 40 mm for wear testing. The pins had smooth surfaces in contact areas and a corner that was adjustable. The test materials were polished with emery sheets and rinsed in acetone before being dried and weighed with an electronic balance with a resolution of 0.001 g before the test. The tests were carried out on a variety of specimens with varying reinforcement and load percentages. Figure 3 depicts the step-by-step technique for determining wear and coefficient of friction.

The wear testing machine is microprocessor operated, and a PC-based information logging system can monitor height loss and frictional force at the same time. The data was collected and the results were shown using Win Ducom software. The test results were seen and assessed using the comparison view tool. A Linear Variable Differential

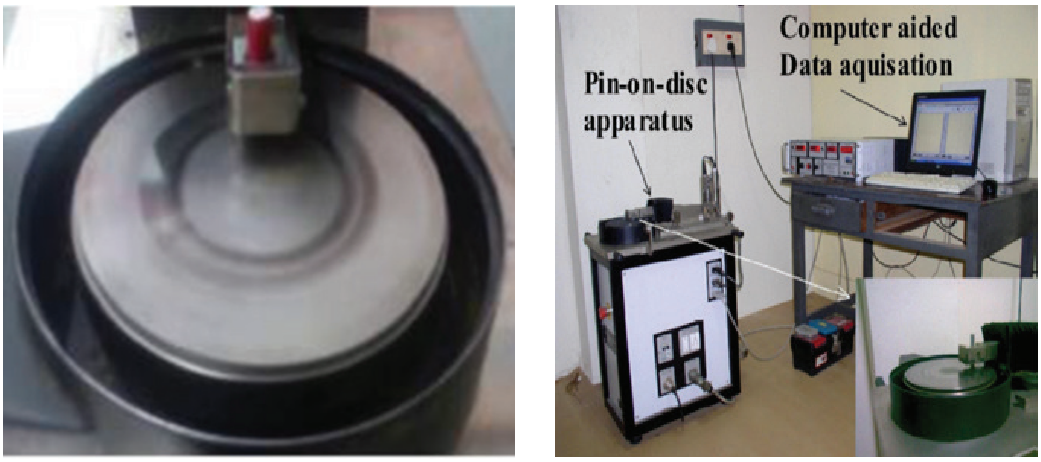


Figure.2 DUCOM Wear and Friction Machine.

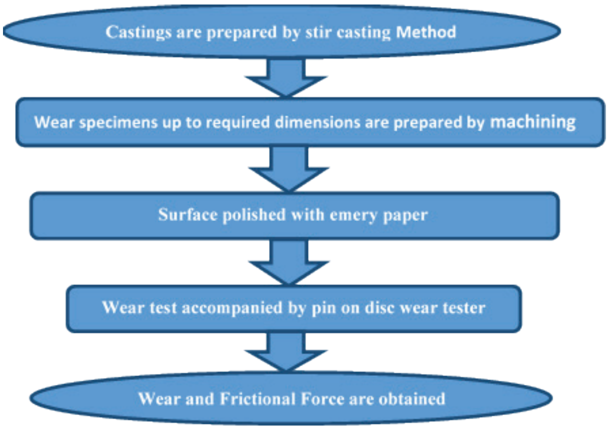


Figure 3. Stage by stage procedure used to evaluate the dry sliding wear.

Transducer (LVDT) was used to estimate the height loss of the pin sample, and a load cell was used to measure the frictional force. Figure 4 shows a sample record of recorded height loss and frictional force as a function of time.

EXPERIMENTAL DESIGN AND OPTIMIZATION

Designs of experiments are used to identify the process conditions and product components that affect quality, and then determine the factor settings that optimize results.

Taguchi Experimentation

Genichi Taguchi, a scientist, developed the Taguchi technique. It is a high-quality design tool for doing repeated experiments, and it reduces variance significantly [7]. Taguchi's signal-to-noise ratios (SNRs) are logarithmic

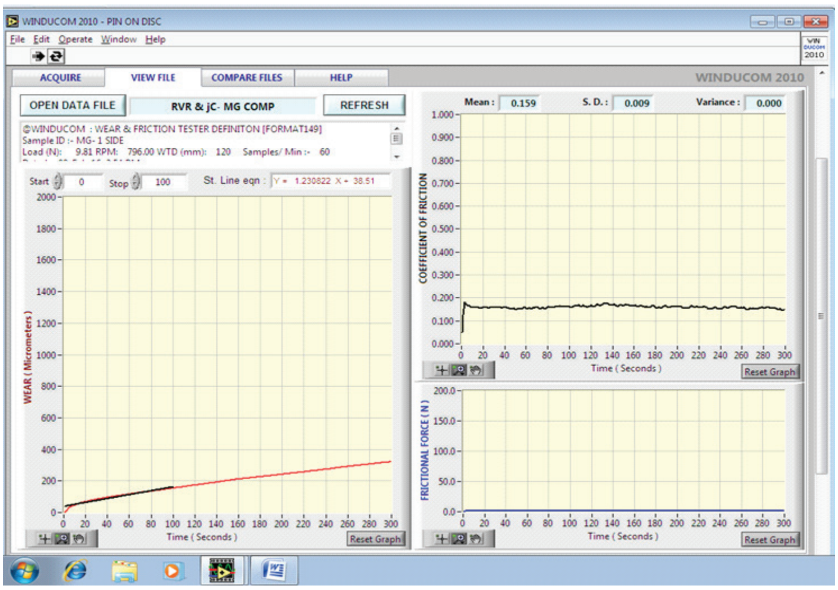


Figure 4. Graphical result on Pin on disc wear tester.

Table 1. Layout of orthogonal array

Experiment. No	Independent Variables			Performance Parameter Value
	S	L	D	
1	1	1	1	p1
2	1	2	2	p2
3	1	3	3	p3
4	2	1	2	p4
5	2	2	3	p5
6	2	3	1	p6
7	3	1	3	p7
8	3	2	1	p8
9	3	3	2	p9

functions of the needed output and serve as an objective function in the optimization process, depending on the number of trials and SNRs. The signal-to-noise ratio (SNR) stands for signal-to-noise ratio. The Taguchi technique can estimate the ideal parameters by considering both the mean and the variability with the aid of SNR. Nominal-is-best (NB), Lower-the-Better (LB), and Higher-the-Better (HB) are the SNR criteria (HB). With the highest SNR ratio, the ideal parameter is treated as the best. In this study, the lower-the-better (LB) option was selected as the responsible variable for both frictional force (FF) and wear (W). With more control parameters, the number of tests to be performed rises, as does the cost of the experiment.

RESULTS AND DISCUSSION

In this work, the Taguchi method is utilized to investigate all wear parameters using the fewest possible tests. Load (L), sliding speed (S), and sliding distance (D) are the most commonly utilized wear parameters [8]. Table.1 lists the parameters and their values. The tests followed the usual orthogonal array protocol. The orthogonal array is chosen based on the constraint that the orthogonal array's degrees of freedom be higher than or equal to the total of those wear parameters. The orthogonal array is chosen based on the need for the degrees of opportunity for the orthogonal array to be more similar to the sum of their wear parameters [3].

In this investigation, a L_9 orthogonal array with 9 rows and 4 columns was favored, as shown in Table.1(i) Sliding speed (S) (ii) Sliding distance (D) (iii) Load (L) are the wear parameters chosen for the tests. The experiment consists of 9 experiments (one for each row in the L_9 orthogonal array), with parameters assigned to the columns represented in Table.1. The wear response will be investigated, with the goal of smaller being better [9,10]. The trials were carried out using an orthogonal array with each row's degree of parameters set.

Evaluation of Experimental Results

The composite pins, which have a 6mm diameter and a 40mm length, are machined smooth for dry slide wear testing [11,12]and manufactured using an EDM method in accordance with ASTM G99-17 requirements. For wear testing, a pin-on-disc machine with a hardened and polished disc as the counter face is employed. The Pins are pressed against the counter face of a revolving disc made with EN-32 steel disc 58-60 HRC track diameter of 100 mm for the wear testing in this test. The load, distance, and

Table 2. Experimental plan and results for wear and C.O.F of Al6351/6%SiC/6%GrMMCs

Test Number	Speed (rpm)	Load (kgf)	Distance(m)	Wear (mm^3/Nm)	C.O.F
1	150	1	1000	59	0.01
2	300	1	1500	76	0.03
3	450	1	2000	79	0.03
4	150	2	1500	60	0.14
5	300	2	2000	81	0.14
6	450	2	1000	106	0.11
7	150	3	2000	96	0.19
8	300	3	1000	100	0.19
9	450	3	1500	110	0.16

velocity of the pins were all taken into account while calculating wear. The sliding speed and distance were calculated using the following relations.

S=(πxdxN/60), where d=Track diameter assumed as 100mm,

N=Speed Considered in rpm

V=D/t where D is the sliding distance in m

The investigative wear and coefficient of friction values are grouped according to the L_9 orthogonal array as shown below (C.O. F). At the time of the experiment, measurement errors were not taken into account, and the average values of three experiments were given for each test number. Table 2 shows the minimal wear and C.O.F. at 150rpm, 1kgf load, and 1000m distance.

Investigation of Data and Prediction of Optimum Levels

The wear and frictional force were calculated using S/N ratio response analysis, which took into account the load, sliding speed and sliding distance separately [13]. The wear rate and frictional force are computed using the principle of "the smaller, the better," as shown in equation.1.

$$\text{S/N ratio} = -10\ \text{Log}_{10}\left[\frac{1}{n}\sum y^2\right] \quad (1)$$

Here n is 1 (wear) & y is value of response (wear value).

The parameter with the highest S/N ratio is considered the best value with the least variance as shown in Table 3. The difference between the maximum and least mean value of S/N ratios was used to determine the impact of parameters. The parameters with the greatest difference in S/N ratios have more impact.

The response tables (Tables 4 and 5) reveal the impact of each control component on wear and C.O.F. The results of the tables show that the load on both wear and C.O.F. is the most impacted parameter.

In general, when the signal to noise ratio is greater than the comparable level of parameter, the performance is at its best. Figures 5 and 6 show the major effect graphs for S/N ratio that are equivalent to wear and friction.

The response tables (Figure 5 and Table 4 show that load is the most important influencing parameter on wear, whereas Figure.6 and Table 5 show that load is the most important influencing factor on friction coefficient. To optimise the condition, the factor levels corresponding to the maximum S/N ratio were chosen. To optimise the condition, the factor levels associated with the highest S/N ratio were chosen. In Table 6, the best parameters for wear are V: 150rpm; L: 1kgf; D: 1500 m, while the optimal values for C.O.F are V: 150rpm; L: 1kgf; D: 1000 m.

Analysis of Variance (ANOVA)

ANOVA is a statistical approach for determining the relevance of each process parameter and estimating the variance error. Fisher's ratio is a variable in ANOVA that is

Table 3. S/N Ratio Analysis

Test Number	Speed (rpm)	Load (kgf)	Distance (m)	Wear (mm3/Nm)	C.O. F	S/N (Wear)	S/N (C.O.F)
1	150	1	1000	59	0.01	-35.4170	40.000
2	300	1	1500	76	0.03	-37.6163	30.4576
3	450	1	2000	79	0.03	-37.9525	30.4576
4	150	2	1500	60	0.14	-35.5630	17.0774
5	300	2	2000	81	0.14	-38.1697	17.0774
6	450	2	1000	106	0.11	-40.5061	19.1721
7	150	3	2000	96	0.19	-39.6454	14.4249
8	300	3	1000	100	0.19	-40.0000	14.4249
9	450	3	1500	110	0.16	-40.8279	5.9176

Table 4. S/N ratio values by factor level corresponding to wear

Level	Load (kgf)	Sliding speed (rpm)	Sliding distance (m)
1	-37.00	-36.88	-38.64
2	-38.08	-38.60	-38.00
3	-40.16	-39.76	-38.59
Delta	3.16	2.89	0.64
Rank	1	2	3

Table 5. S/N ratio values by factor level corresponding to C.O.F

Level	Load (kgf)	Sliding speed (rpm)	Sliding distance(m)
1	33.64	23.83	24.53
2	17.78	20.65	21.15
3	14.92	21.85	20.65
Delta	18.72	3.18	3.88
Rank	1	3	2

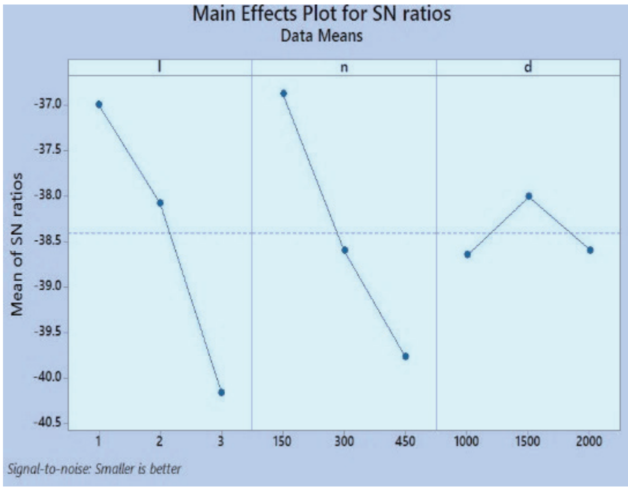


Figure 5. Effect plots for S/N ratios equivalent to wear.

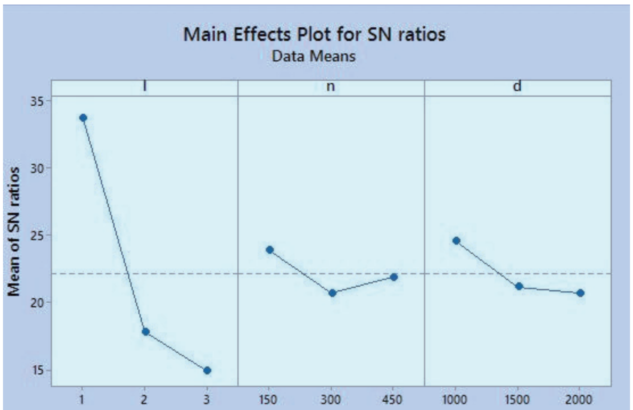


Figure 6. Effect plots for S/N ratios equivalent to C.O.F.

defined as the ratio between the variance factor and variance error. It is useful to compare the F test value to the conventional F table value (F) with a percent significance threshold. The influence of the control factor is determined by the F-ratio. ANOVA was used to analyze the effect of control factors on wear and friction force. The results of ANOVA for wear and coefficient of friction are presented in Tables.7 and 8. For this study, a significance level of 0.01, i.e. a level of confidence, was used.

The error will be treated as zero in this project. As a result, an erroneous sum of squares is calculated by combining all of the squares corresponding to the components with the lowest mean square. The sum of squares referring to the base component of the variables (as defined by lower mean square) is used to analyze the error sum of squares as a reliable guideline (rule of thumb). The wear velocity will have the least mean square, as will the coefficient of friction, and the sum of squares for these parameters will be pooled to error. The F value [14] is calculated using this error.

The parameter load (L) makes the major support the entire sum of squares [(1410.67/2845.56) x 100 = 49.57 percent according to ANOVA results indicating the sum of squares in Table 7. The sliding velocity (V) parameter contributes the most to the overall sum of squares (37.48%), whilst the sliding distance (D) parameter contributes only 0.4 percent. The greater a factor's contribution to the total sum of squares, the greater that factor's capacity to impact wear. In addition, compared to the error mean square or error variance, the bigger the F-value, the larger the factor effect.

Similarly, referring to the sum of squares in Table 8, the factor Applied load (L) makes the biggest support to the total sum of squares [(0.036817 /0.039889) x 100 = 92.29%]. The factor (D) makes the next biggest support (1.045%) to the total sum of squares, while the factor (S) only 0.66% support. The larger the support of a particular factor to the total sum of squares, the larger the ability is of that factor's impact on coefficient of friction. Additionally, the larger the F-value, the larger will be the factor's influence in comparison to the error variance or the error mean square.

Table 6. Optimal Values for Wear and C.O.F

Factor	Optimal Wear Values	Optimal C.O.F Values
Sliding Speed (rpm)	150	150
Applied Load (kgf)	1	1
Sliding Distance (m)	1500	1000

Table 7. ANOVA table for Wear

Parameter	DOF	Sum of squares	Mean square	F-value	P-value	% of Contribution
L	1	1410.67	1410.67	19.88	0.007	**49.57**
S	1	1066.67	1066.67	15.04	0.012	**37.48**
D	1	13.50	13.50	0.19	0.681	**0.4**
ERROR	5	354.72	70.94			
TOTAL	8	2845.56				

Table 8. ANOVA table for C.O.F

Parameter	DOF	Sum of squares	Mean square	F-value	P-value	% of Contribution
L	1	0.036817	0.036817	77.06	0.000	**92.29**
S	1	0.000267	0.000267	0.56	0.489	**0.66**
D	1	0.000417	0.000417	0.87	0.393	**1.045**
ERROR	5	0.002389	0.000478			
TOTAL	8	0.039889				

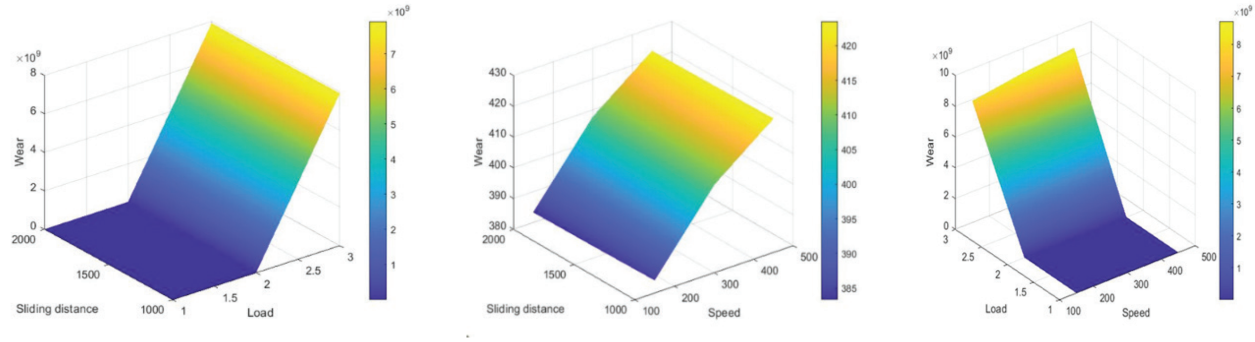
Regression Analysis

The key process response characteristic in this study was the coefficient of friction and wear, which was used to analyse the impact of parameters using a mathematical model. The influence of sliding speed (S), sliding distance (D), and applied load (L) [15,16] on wear and coefficient of friction (C.O.F) of aluminium composites was calculated using Multiple Linear Regression Analysis (MLRA) [17]. A mathematical model was constructed to relate process control parameters to response characteristics. Multiple linear regression analysis was used to develop a mathematical model for estimating wear and coefficient of friction in terms of the governing parameters. These equations were created to forecast the future.

$$\text{Wear} = 10^{2.4}.\ S^{0.0889}.\ L^{15.33}.\ D^{-0.00300} \quad (2)$$

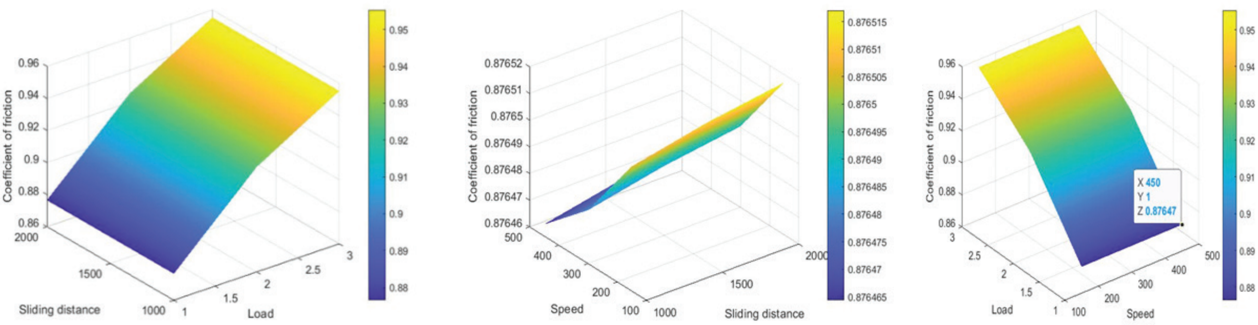
$$\text{C.O. F} = 10^{-0.0572}.\ S^{-0.000044}.\ L.^{\ 0.07833}\ D^{0.000017} \quad (3)$$

Figure 7 shows the variation of wear with three influencing factors based on Eq.2. The wear increased with the increasing of load, speed and distance, the wear is lowest under lower load (L = 1kgf), speed (S= 150rpm) and distance (D= 1000m). (Figure 7(a)). With the increase of distance and load, the wear is increased at constant speed, and the wear under high speed and distance is higher at constant load (Figure 7(b)). The impact of sliding speed and load on wear is more at constant distance. The wear increases with increasing sliding speed and load (Figure



(a) (b) (c)

Figure 7. Variation of Wear vs Sliding Distance, sliding speed and Load



(a) (b) (c)

Figure 8. Variation of C.O.F vs Sliding Distance, sliding speed and Load.

7(c)). The analysis shows that the impact of three factors on the wear is coupling effect, there is correlation among them.

Figure 8 shows the variation of c.o.f with three influencing factors based on Eq. 3. The coefficient of friction (c.o.f) increased with the increasing of load, speed and distance, the c.o.f is lowest under lower load (L = 1kgf), speed (S = 150rpm) and distance (D = 1000m). (Figure 8(a)). with the increase of distance and load, the c.o.f is increased at constant speed, and the c.o.f under high speed and distance is higher at constant load (Figure 8(b)). The impact of sliding speed and load on c.o.f is more at constant distance. The c.o.f increases with increasing sliding speed and load (Figure 8(c)). The analysis shows that the impact of three factors on the c.o.f is coupling effect, there is correlation among them.

Estimation of Optimum Wear and Coefficient of Friction (C.O.F)

With the procedure of Taguchi optimization, a validation analysis was necessary to be directed for approving of the optimized condition [18-20]. The Equations (4) and (5) are used for the valuation of optimal wear and coefficient of friction respectively.

$$W\,(opt) = (L_1\text{-}W) + (S_1\text{-}W) + (D_2\text{-}W) + W \quad (4)$$

$$C\,(opt) = (L_1\text{-}C) + (S_1\text{-}C) + (D_1\text{-}C) + C \quad (5)$$

Bold values shows the W and C values attained from test study

To get the optimized results the conditions were utilized for the determination of the confidence interval(CI) for evaluated wear and coefficient of friction [21,22, 23,24,25]:

$$CI_{w,\,c}=\sqrt{F_{\alpha,1,fe} V_e \left[\frac{1}{N_{eff}} + \frac{1}{R}\right]} \quad (6)$$

And

$$N_{eff}=\frac{N}{1+T_{dof}} \quad (7)$$

The input data for equations (6) and (7) are tabulated in Table 10 as

Here, $F_{\alpha,1,fe}$ is the F ratio is at a confidence of 95%, α is the level of significance, is f_e the error degrees-of-freedom, V_e is variance error, N_{eff} is the effective number of replications, R is the replications number for confirmation experiments (Eq.(6)). N is total experiments number, and T_{dof} is the total main factor degrees of freedom Eq. (7).

$F_{0.05,\,1,\,5}$ = 6.6079 (from F test table),
V_e (W) = 70.94 and
V_e (c.o.f) = 0.000478 (Table 5.7),
R =1 (Eq. (6)).
N = 9,
T_{dof}= 3 and
N_{eff} = 2.25 (Eq. (7)).

By utilizing the Equations. (6) and (7) the confidence intervals were determined as

CI-W = 58.18523 and CI-C =0.151036.

The estimated average optimal wear and coefficient of friction (C.O.F) with the confidence interval at 95% confidence is:

Optimum test result of Wear:

$[W_{opt}\text{-CI-W}] < W_{exp} < [W_{opt}\text{+CI-W}]$;
[56.09667-58.18523] <84.45167< [56.09667+5818523];
-2.08856<84.45167<114.2819.

Table 9. Mean responsible table for wear and coefficient of friction (C.O.F)

Mean responsible table for wear and coefficient of friction (C.O.F)						
Levels	**Control Factors**					
	Wear			**Coefficient of Friction (C.O.F)**		
	L (kgf)	**S (rpm)**	**D(m)**	**L (kgf)**	**S (rpm)**	**D (m)**
Level1	71.66667	71.33333	88.33333	0.113333	0.023333	0.103333
Level2	85.66667	82.33333	82	0.12	0.13	0.11
Level3	98.33333	102	85.33333	0.114	0.18	0.12

Table 10. Input Data

Fα	fe	Ve	Neff	R	N	Tdof
6.6079	5	70.94	2.25	1	9	3
6.6079	5	0.000478	2.25	1	9	3

Optimum test result of C.O.F:

$[C_{opt}\text{-CI-C}] < C_{exp} < [C_{opt} + \text{CI-C}]$;

[0.017778-0.151036] <0.111111< [0.017778+0.151036];

-0.13326<0.111111<0.168814.

The experimentally obtained Wexp and Cexp values stayed within the confidence interval ranges. As a result, the Taguchi approach was used to optimize the system for wear and coefficient of friction at a significance level of 0.05 [26,27]. At optimum levels, validation tests of the control parameters were conducted using the Taguchi method [28-30]. The experimental and calculated optimal values are very close to each other. As a result, the validation test results reflect successful optimization.

$$\text{Wear} = 2.4 + 15.33\,L + 0.0889\,S - 0.00300\,D \quad (8)$$

$$\text{C.O.F} = -0.0572 + 0.07833\,L - 0.000044\,S + 0.000017\,D \quad (9)$$

The best combination of experimental parameters for achieving a low coefficient of friction and a low wear rate is Speed=150 rpm, Load=1kgf, and Distance=1000m. Equations 8 and 9 can be used to calculate the ideal level of design parameters: Table.11 shows the results of a confirmation test for the best combination of wear characteristics using various combinations of load, distance, and speed.

Table 12 shows a comparison of estimated and experimental output responses for wear with the optimal cutting parameter combination and a reference level. The analysis shows that using the optimal parameter values (150,1,1000) resulted in a lower wear rate than using other parameter combinations.

Table 11. Combination of wear parameters

Parameters	Combination of parameters		
Sliding Speed (rpm)	150	450	300
Load (kgf)	1	3	2
Distance (m)	1500	1000	1500

Table 12. Results of confirmation test

Response	Experimental value	Normalized value, X*	Deviation value, Δ
Wear	65	64.5	0.5
	86	85.395	0.605
	61	58.88	2.12
C.O.F	0.02	0.015	0.005
	0.15	0.14	0.01
	0.13	0.11	0.02

CONCLUSIONS

Taguchi and Multiple Linear Regression Analysis were used to find the best conditions for the parameters that influence the coefficient of friction and wear. In this part, the testing findings for wear and coefficient of friction of hybrid composites were displayed. The following are the results using Mini Tab software: S: 150rpm; L: 1kgf; D: 1500. V: 150rpm; L: 1kgf; D: 1000 m have the same coefficients of friction. The percentage of contribution of parameters was determined using an ANOVA analysis. The influence of each parameter can be identified by ANOVA (Analysis of variance) technique. For Wear the parameter load (L) makes the major support the entire sum of squares 49.57 percent while sliding speed (S) 37.48% and sliding distance (D) contributes only 0.4 percent and the factor Applied load (L)92.29% makes the biggest contribution in frictional force according to ANOVA. Finally, it is determined that load and speed are the most important elements influencing wear rate. Load and distance are more important elements when it comes to coefficient of friction.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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