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Analysis on Wear Parameters of Boron Carbide Embedded Aluminium Matrix Composites (413/B₄C) using Taguchi Technique

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Abstract

Aluminium matrix composites (AMCs) are widely used across a variety of sectors, including electronics, automobiles, aircraft, and offshore, due to their outstanding mechanical properties, including high strength, low weight, and corrosion resistance. However, applications that require high tribological efficiency are challenged by their low wear resistance. The investigation of the statistical approach to the wear properties of 413/B₄C

composites is presented. Three, six, and nine percent B_4C -reinforced AMCs were prepared by stir casting. The wear was examined in multiple environments of Sliding Speed, S (1 m/s, 1.5 m/s, and 2 m/s), Sliding Distance, D (500 m, 1000 m, and 1500 m), applied load, L (15 N, 30 N, and 45 N), and reinforcement %, R (3, 6 and 9%). The L_{27} Orthogonal array (OA) was chosen to assess responses such as SWR & COF, and Taguchi's approach was implemented to optimise the wear factors. Further, by selecting the "smaller is better" feature, analysis of variance (ANOVA) was used to analyse the impact of input factors on wear performance. According to this investigation, the most appropriate SWR values are S – 1 m/s, D – 1000 m, L – 45 N, and R% – 9 wt. % B_4C and the optimal values of COF are S – 2 m/s, D – 500 m, L – 15 N, and R% – 3 wt% B_4C . Applications that demand high wear resistance and low friction can benefit from the optimised performance characteristics of premixed reinforcement composite materials.

Key words: Sliding wear, Composites, Specific Wear Rate, COF, ANOVA, Taguchi

1. Introduction

In the 1970s, fiber reinforcements were added to metal matrix-based composites [1]. Alloys are utilized extensively in the automotive, aircraft, and mineral extraction industries because they offer several advantages, including excellent durability, light weight, and environmental resilience. The structural strength and hardness of aluminium matrix composites are often higher than those of pure aluminium alloys. Furthermore, it has been demonstrated that the use of AMCs can significantly enhance tribological characteristics, particularly resistance to sliding, abrasive wear, and seizure [2, 3]. Nevertheless, AMCs frequently have reduced fracture toughness and ductility. A tougher material contacting a metal face and repeatedly sliding or impacting it causes abrasive wear, a type of frictional wear that removes material. Because of the longitudinal ridges that form on the smoother layer, it is the most prominent kind of wear and is frequently called scratching. This wear phenomenon is frequently observed when metal parts are exposed to abrasive particles, such as sand, in manufacturing environments [4]. The braking system is the primary safety feature of automobiles. The disc brake system is currently the most popular brake type in the automotive industry. The fundamental concept is to use the loss of kinetic energy into heat to accelerate the vehicle safely. As a result, the brake system's temperature rises, and wear debris is produced. Worn debris may become airborne or fall to the soil, depending on its size. They are demonstrated to have detrimental effects on both the natural world and human wellness in both circumstances [5-10].

In the mining sector, abrasive wear caused by hard-particulate fabrication results in significant financial losses [11]. Composites with inflexible dispersoids and a relatively soft matrix are frequently used to extend the lifetime of large material-handling tools, such as chute wear liners [12, 13]. The combined effects of essential qualities enable composites to exhibit stronger wear resistance than their constituent elements alone. For instance, one popular method to improve resistance to abrasive wear is to embed hard carbides in a softer matrix [14, 15]. The hard particles' role as load-bearing elements represents a hypothesis offered to explain the increase in wear resistance [16]. In passenger vehicles regularly driven on unpaved roads, cut-and-chip wear may be the most common form of wear. The size of debris from wear fragments usually increases from nanometers to centimeters [17-19]. To reduce the incidence of intricate cut-and-chip events in the field, it is necessary to research and understand them [20]. A tremendous quantity of heat builds up at the tool-chip interface during processing [21-23]. Crater and flank wear are the two primary forms of tool wear brought on by heat generation. These wear modes shorten the tool's lifespan and cause dimensional errors, surface degradation, and severe corrosion on the workpiece [24, 25]. The process thus gets more expensive and intricate [26]. Additionally, cutting fluids account for 7-17% of manufacturing costs. Manufacturers worldwide use over 38 million tons of lubricants, and this figure is predicted to rise by 1.2% every 10 years [27, 28].

The impact of SiC particulate dispersoid on the composites made of ZA27 alloy was documented by Sharma et al. The applied 'L' and 'S' were changed during the tests. Based on the data, the wear rate decreases as the proportion of dispersoid increases. Particle fracturing and delamination were noted as wear processes [29, 30]. The impact of normal 'L' and the 'S' of wear and friction on the characteristics of an aluminium disc in contrast to a stainless-steel pin was examined by Chowdhury et al. [31]. The findings demonstrated that the COF improved as the 'S' increased. It was also found that when 'S' and the normal 'L' increased, the wear rate correspondingly increased. According to Sap et al. [32], wear rose as the sliding velocity and normal load increased. Hardness is correlated with adhesion and friction, and it increases with either a steady or a random increase in SiC particles. As a result, each metal's wear rate is influenced by high-load conditions and is not related to corrosion resistance in less demanding conditions. A long, uncontrolled sliding distance and increasing load affect the rate of wear in sliding wear. Kumar et al. [33] investigated the wear behaviour of the zinc-aluminum (ZA-27) alloy. Wear resistance increased as garnet concentration increased, which is thought to be one of the factors influencing the oxide layer. It is feasible to create a customised composite by carefully choosing the right matrix and dispersoids. Al and its alloys have received greater attention due to their extensive use in

the automotive industry [34]. Hybrid composites can be effectively developed using dispersoids such as fly ash, graphite, B_4C , red mud, SiC, and TiO_2 [35-38].

The liquid metallurgical process can generate reinforced particles with an invariant distribution, low cost, and improved intermolecular interactions among the continuous phase and dispersoid [39-41]. The Taguchi strategy is a statistical method of investigation that adds a new dimension to traditional experimentation by conducting a small number of experiments using an orthogonal array. Large-scale wear experiments that consider variables including 'L', 'S', % reinforcement, time, and 'D' have employed pin-on discs [42]. The main variable affecting the wear properties can be identified using ANOVA. The current experimental effort optimises input control parameters to produce responses characterised by minimal SWR and COF using the Genichi Taguchi DoE. The input controlling variables are 'S', 'D', 'L', and reinforcement; the output responses are SWR and COF. There is a restriction on the number of trials that can be conducted using L_{27} orthogonal arrays, and the optimisation objective functions are signal-to-noise ratios (S/N). A confirmatory test was used to validate the linear regression model.

There is a limited wear study exist on aluminium matrix, Boron carbide composites because of the formation of brittle phases which may deteriorate the toughness of the composites and thus wear resistance. In general, Al 413 has moderate wear resistance but relatively soft. Boron carbide has superior hardness and neutron absorption rate compared to other carbides whereas it has poor wettability and interfacial reactivity which may affect the wear resistant properties. Poor wettability of the composite may affect the load transfer efficiency among the Al 413 and B_4C which will increase the wear rate and the detached B_4C particles act as abrasives. The larger difference in thermal expansion between the matrix and reinforcement may induce crack at the interface. These are the challenges associated with the Al413/ B_4C composites. The novelty of the presented work lies in the usage of the reinforcement. In order to get good wettability and interfacial reactivity, wetting agent K_2TiF_6 was added in this study. Most of the researchers focused on either SWR or COF independently but the presented work focused on SWR & COF simultaneously. In this investigation, four input variables are optimized simultaneously which gives comprehensive investigation on process parameters and their effects. It is believed that the optimization of wear variables may increase the component life and reduce the maintenance cost.

2. Experimental Details

2.1 Materials

2.1.1 Aluminium Alloy (413)

Aluminium alloy (413) is difficult to process due to its tendency to drag and, as a result, its high silicon concentration, which accelerates tool wear. The aluminium alloy (413), in both normal air and marine environments, has exceptional corrosion resistance. Unlike the other casting alloys, it can be cast into progressively intricate and thin parts. Table 1 displays the composition of 413 aluminium alloy.

Table 1. Elemental Analysis of Aluminum Alloy 413 Matrix Material

Constituent	Si	Cu	Fe	Mg	Mn	Ti	Ni	Zn	Al
Weight %	11.48	0.013	0.52	0.02	0.01	0.02	0.01	0.01	Remainder

2.1.2 Boron Carbide

For this investigation, 63 micron-sized boron carbide (B_4C) particles served as dispersoid. B_4C is frequently utilised as a cermet and armour material due to its numerous beneficial features. In a nuclear reaction, the optimal material for neutron absorption is one with a high cross-section that does not produce any radioactive isotopes after neutron capture. The isotope B10 of boron, which occurs naturally, has a cross section of 755 barns. As a result, boron is particularly well-suited for nuclear applications. Figure 1 depicts the surface structure of B_4C particles. The addition of nano sized B_4C in the aluminium matrix may lead to aggregation of reinforcement. This will affect the strength of the composites and thus wear resistance. The micron sized B_4C is easy to disperse homogeneously because of less surface energy. Further, it acts as a barrier to dislocation motion within the matrix which increase the yield strength and microhardness. Hard ceramics protect the matrix from abrasion and hence significantly reduce the wear rate & COF. The load bearing capacity of the matrix also enhances with the presence of hard micron sized B_4C particles.

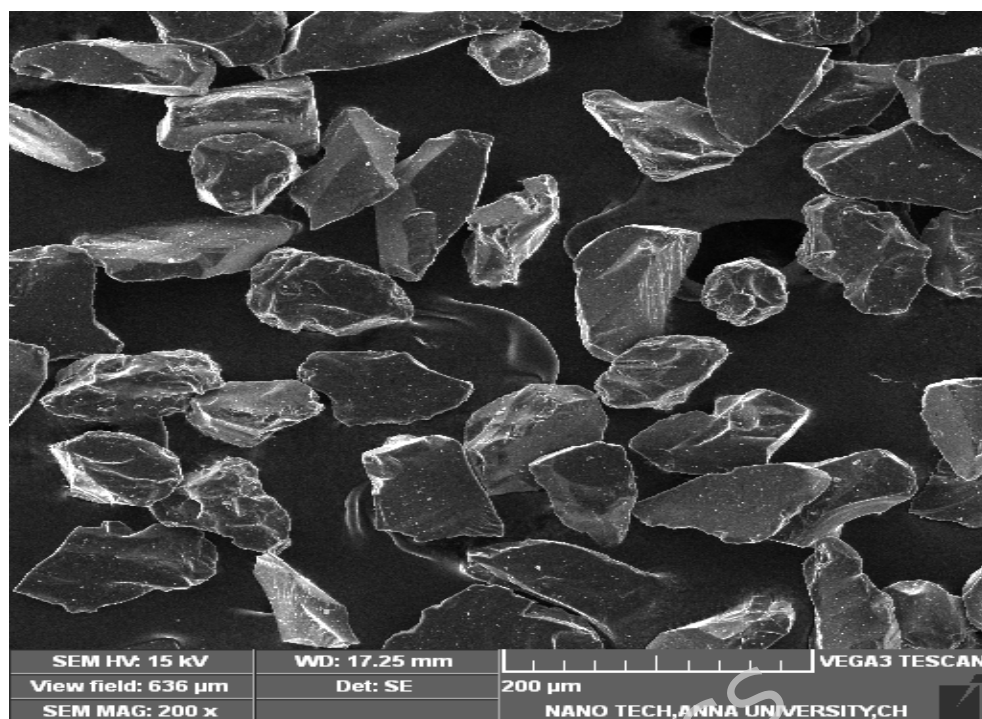


Figure 1. Morphological Characteristics of B₄C Reinforcement Particles

2.2 Fabrication of Al Alloy 413 / B₄C Composites

An electric furnace was employed to melt the aluminium alloy 413 flakes in a graphite crucible. The temperature slowly rose to 850 degrees Celsius. Using a degasser, the melt was made free from gases. The B₄C particles (250 °C) were incorporated after the hot metal was carefully stirred to create a vortex. For 10 minutes, the slurry was being stirred at 600 rpm. Potassium (K) and fluoride (F) help to eliminate the O₂ layer from the Al surface when titanium (Ti) is added as K₂TiF₆. Due to the extremely low Ti content (<1% by weight), the matrix alloys' characteristics remained largely unchanged. Three, six, and nine percent by weight of boron carbide was added. The hot slurry was transferred into preheated cast iron moulds at 650 degrees Celsius and left to cool to room temperature. Figure 2 shows the stir casting setup.



Figure 2. Schematic of the Stir Casting Setup and Furnace Assembly

2.3 Design of Experiments (DoE)

2.3.1 Taguchi Approach

The Taguchi approach, which applies structured investigations, has become admired for quality engineering in production processes to understand product/process differences with the fewest possible tests. Its application, in other words, makes process/product development more cost-effective [43, 44]. Depending on the S/N ratio computation, the Taguchi design aims to optimise the process variables for enhanced efficiency. To achieve high quality at a low cost, the Taguchi technique relies heavily on parameter design. Many investigations must be conducted in a classical factorial design as the number of variables increases. For instance, a Taguchi design requires only 8 experiments, whereas a full factorial design with 7 variables and a 2-level design requires 128 experiments [45, 46]. Each row in an orthogonal array arrangement reflects the underlying condition, while the vertical columns reflect all the variables listed in the investigation. The Taguchi approach analyses using the three quality features: the lower the better, the higher the better, and the nominal the best. The S/N ratio is assessed for every process variable level using S/N analysis. The process variable with the highest S/N ratio is the best. Additionally, the statistical significance of the process variables is assessed using analysis of variance (ANOVA). To confirm that the ideal process variables derived from the parameter design, a validation experiment was finally conducted. When selecting process variables, the material properties and their influence on input process variables with limited machine levels were considered. The machining parameters and their corresponding levels are displayed in Table 2.

Table 2. Selected Experimental Parameters for Al413 Reinforced with B₄C Particles

Level	S (m/s)	D (m)	L (N)	R%
1	1	500	15	3
2	1.5	1000	30	6
3	2	1500	45	9

2.3.2 ANOVA

ANOVA is used to assess the statistical significance of parameters and their effects at the 95% confidence level after the best process parameters have been determined [47, 48]. A confirmation experiment was then conducted based on the design specifications. Multiple linear regression models are then created to establish interactions among the process variables and the response characteristics. The created models enable the prediction of responses within the variables under investigation.

2.4 Regression Analysis

Regression analysis is performed on the resulting experimental analysis according to the OA. Regression analysis enables the creation of predictive models that link outcomes to the factors under investigation [49]. Regression models are statistical tools used to investigate the relationship between multiple independent variables and a dependent variable [50]. For both responses SWR and COF, a multivariate regression model was built using the variables "S," "D," "L," and "R". To determine the system's adequacy, the corresponding coefficients of determination (R^2) were computed; R-squared values typically fall between 0% and 100% and have an interval of 0 to 1. A basic guideline for acceptable R-squared was put forth by Henseler et al. [51], with 0.75, 0.50, and 0.25 designated as significant, medium, and weak, respectively. Accordingly, an insignificant effect size is generally defined as $0.25 < r < 0.5$, an adequate effect size as $0.5 < r < 0.75$, and a large effect size as $R^2, r > 0.75$. The model becomes more significant as the R^2 value increases or approaches 1. Moreover, R-Sq. (adj) values are over 80%, indicating that developed models are both practical and sufficient to forecast the output taken into consideration within the range of wear process variable levels. Moreover, regression model fits were verified by comparing them with experimental findings [52].

2.5 WEAR MEASUREMENT

Figure 3 depicts the pin-on-disc arrangement used to investigate the wear characteristics of composites and Table 3 shows the Technical Specifications of Pin on disc equipment.



Figure 3. Photographic View of the Pin-on-Disc Tribological Testing Machine

Table 3. Experimental Specifications of the Pin-on-Disc Apparatus Used for Tribological Evaluation

Disc rotation speed	0 - 1500 rpm
Load	0 - 60 N
Frictional Force	0 - 60 N
Pin Diameter	2 - 10 mm
Pin Length	30 - 60 mm
Disc Diameter	30 - 100 mm
Disc Thickness	10 mm
Temperature	ambient - 550° C

2.5.1 Test Specimen and Sample Preparation

Pins with an overall diameter of 6 mm and a length of 40 mm are produced from stir-cast composites and finished to a surface quality of approximately 0.5 μm . To test composites, AISI 4140 steel discs with a diameter of 55 mm, a thickness of 10 mm, and a hardness of 55 HRC are processed to a surface roughness of approximately 0.5 μm . The image of the prepared sample is shown in Figure 4.

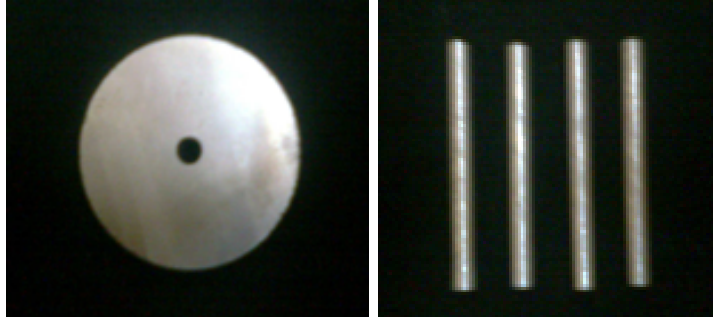


Figure 4. Prepared Composite Specimen of Al413 Reinforced with B₄C Particles

2.5.2 Test Procedure

The wear tests were conducted at ambient temperature under dry sliding conditions. Acetone was used to sterilise the pin and disc components before analysis and measurements to eliminate any dirt from the sample. A digital weighing machine was utilised to measure the sample's weight reduction before and after the wear test. The pin is firmly placed in its Fixture and fitted so that the sample and the disc surface are aligned after the disc is firmly set on the holding equipment. To provide an appropriate effect, the pin face is placed towards the disc, and mass is incorporated into the system lever. The pin sample was kept away from the disc surface while the motor was activated, and the velocity was reduced to the appropriate level. The desired value has been pushed into the timer. The specimens are in contact with each other under load when the test begins. When the target time is reached, the test is immediately terminated.

3. Results

3.1 Density and Porosity

The following formula was employed to determine the porosity of the composites.

$$\text{Porosity \%} = \frac{\text{Theoretical Density} - \text{Measured Density}}{\text{Theoretical Density}} \times 100$$

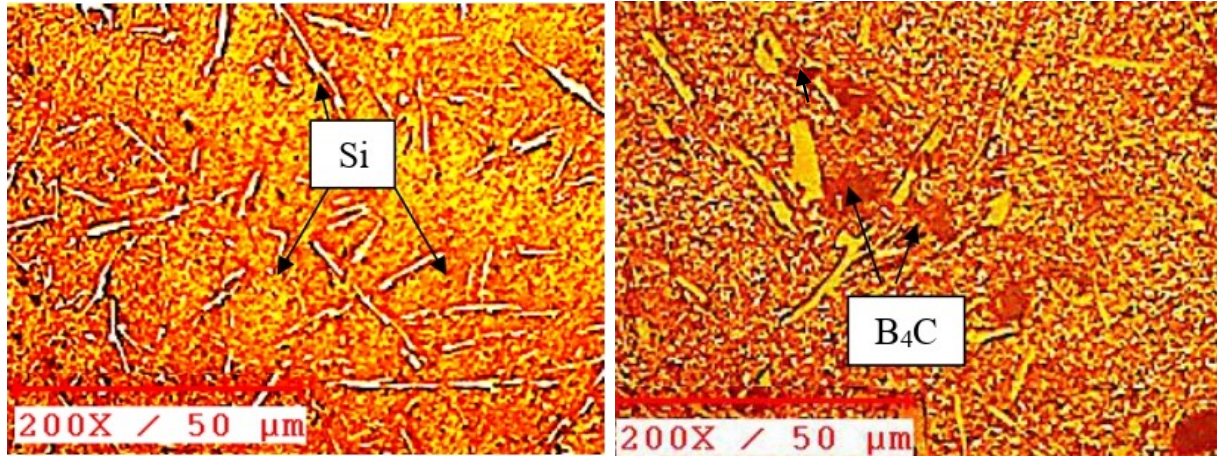
Table 4 presented the composite materials' porosity and density values. The results obtained from the measurements of the densities agree with their theoretical predictions. The porosity is the cause of the very slight discrepancy. The results show that as particulate loading is higher, the porosity percentage rises. It is consistent with the findings documented in the literature. Stir casting requires a longer stir time, which increases gas absorption when adding more dispersoids to the continuous phase.

Table 4. Density and Porosity Evaluation of Al413/B₄C Fabricated Specimens

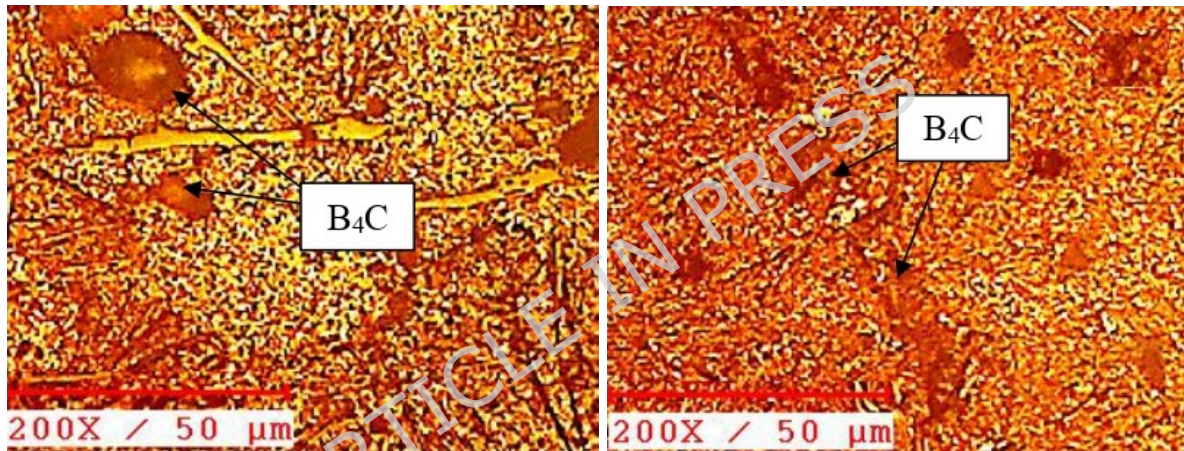
Sl. No.	Material	Theoretical Density (g/cm ³)	Measured Density (g/cm ³)	Porosity (%)
1	413+3%B ₄ C	2.69	2.69	0.17%
2	413+6%B ₄ C	2.69	2.62	2.57%
3	413+9%B ₄ C	2.68	2.5	6.85%

3.2 Microstructural Studies

The materials' microstructure is shown in Figure 5. Figure 5a illustrates the uniform particle dispersion in aluminium 413 alloys. The presence of high Si content in aluminium 413 alloys retain this specific consistently distributed arrangement. 413's eutectic constituents are script-shaped, lengthy, acicular, and unaltered. The dispersion of 3% B₄C in the Al matrix is displayed in Figure 5b. The microscopy image of a composite with 6% and 9% reinforcement is shown in Figure 5c and d, respectively. They are differentiated in the continuous phase by their contrast in light and dark colours and particle sizes. Metallographic analyses are a significant investigative tool and a potent quality control method. To achieve a mirror-like surface, the samples were sliced from each composite and then finely polished. The primary goal of the microstructural examination is to ensure that dispersoid particulates are homogeneously distributed throughout the continuous phase.



a, Aluminium Alloy 413 b, Aluminium Alloy 413+3% B₄C



c, Aluminium Alloy 413+3% B₄C d, Aluminium Alloy 413+3% B₄C

Figure 5 (a-d). Microstructural Analysis of Aluminum Matrix Composites Reinforced with B₄C Particles

3.3 Taguchi's OA experimentation

The experimental findings of 413/Boron Carbide AMCs' wear behaviour are depicted in Table 5. The purpose of the testing is to examine how machining variables affect the response features, specifically SWR and COF. Minitab statistical software was used for all designs, graphs, and analyses in this study. The 27 rows of the L₂₇ orthogonal array, with three distinct levels and 13 columns, correspond to the number of investigations. The experiment was repeated thrice and the average value was given in Table 5.

Table 5. Tribological Performance: Experimental SWR and COF Results of Al413/B₄C Composite

Expt. No.	S (m/s)	D(m)	L (N)	R (wt %)	SWR $\times 10^{-5}$ (mm ³ /Nm)	COF	S/N for SWR	S/N for COF
1	1.0	500	15	3	9.92	0.098	80.07	20.18
2	1.0	500	30	6	4.98	0.305	86.05	10.31
3	1.0	500	45	9	3.33	0.418	89.56	7.58
4	1.0	1000	15	6	12.46	0.524	78.09	5.61
5	1.0	1000	30	9	7.48	0.472	82.52	6.52
6	1.0	1000	45	3	4.13	0.455	87.67	6.84
7	1.0	1500	15	9	9.98	0.378	80.02	8.45
8	1.0	1500	30	3	10.75	0.547	79.37	5.24
9	1.0	1500	45	6	8.30	0.478	81.61	6.41
10	1.5	500	15	6	14.95	0.469	76.51	6.58
11	1.5	500	30	9	7.48	0.307	82.52	10.26
12	1.5	500	45	3	4.96	0.437	86.09	7.19
13	1.5	1000	15	9	9.98	0.433	80.02	7.27
14	1.5	1000	30	3	11.16	0.491	79.05	6.18
15	1.5	1000	45	6	8.30	0.421	81.61	7.51
16	1.5	1500	15	3	9.92	0.493	80.07	6.14
17	1.5	1500	30	6	9.96	0.41	80.03	7.74
18	1.5	1500	45	9	8.87	0.446	81.04	7.01
19	2.0	500	15	9	9.98	0.204	80.02	13.81
20	2.0	500	30	3	7.44	0.195	82.57	14.20
21	2.0	500	45	6	9.96	0.352	80.03	9.07
22	2.0	1000	15	3	9.92	0.375	80.07	8.52
23	2.0	1000	30	6	3.74	0.455	88.55	6.84
24	2.0	1000	45	9	2.49	0.445	92.06	7.03
25	2.0	1500	15	6	11.63	0.578	78.69	4.76
26	2.0	1500	30	9	8.32	0.382	81.60	8.36
27	2.0	1500	45	3	10.47	0.478	79.60	6.41

3.3.1 Evaluation and Discussion of SWR's Findings

The Taguchi method's parametric approach was used to conduct the wear testing. This section examined the impacts of specific process variables on the chosen quality features, such as SWR and COF. Based on the experimental findings, the S/N ratios of the response features for each parameter at various values were computed. The primary effects of the process factors on the S/N data were plotted. To determine the significant parameters and assess their impact on the response qualities, an ANOVA of the S/N data is performed.

By examining the graphs and the ANOVA table, the most advantageous values of machining parameters with respect to mean response features are determined. This experiment is targeted to minimize the response so that higher S/N ratio is better.

A parameter has no apparent effect if its line in the main effect plot is close to the horizontal (flat line). On the other hand, a variable with the steepest line, which has the highest inclination, has the most impact. In this instance, the parameters "L," "D," "R," and "S" had the biggest impact on the wear rate. Figure 6 illustrates, how the SWR rises with increasing 'S' and 'D' and drops with increasing 'L' and 'R %'. The composite is wear-resistant due to its extremely hard boron carbide particles. SWR is not as significantly impacted by sliding speed.

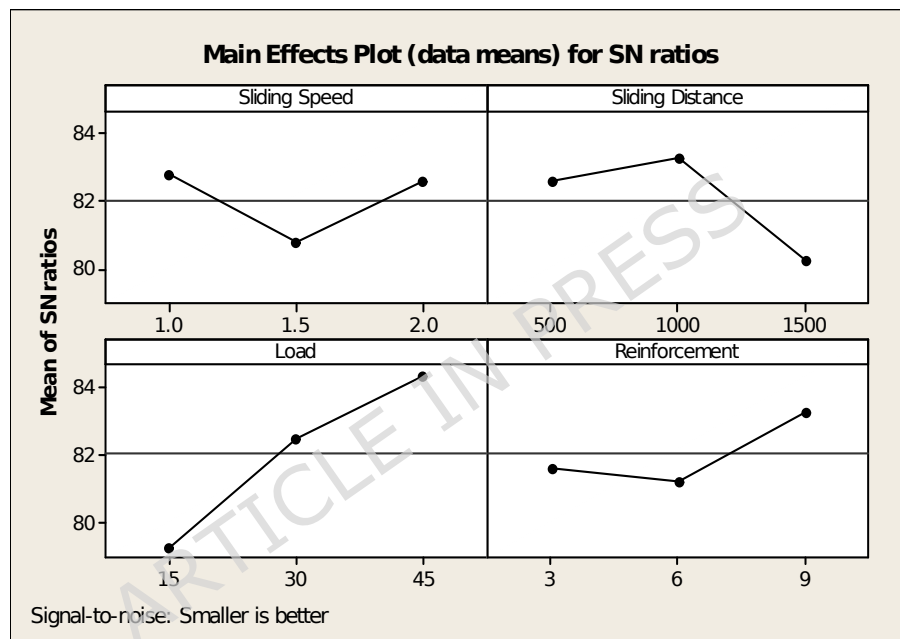


Figure 6. Response Graphs Illustrating the Effect of Process Parameters on SWR of 413/B₄C Composite

3.3.2 Residual Evaluation of S/N Ratio-Based SWR

To determine how well a statistical approach for the Signal-to-Noise (S/N) ratios fulfils the requirements required to perform reliable estimation, residual diagnostic plots are utilised. The discrepancies between observed and model-predicted values are known as residuals. Figure 7 shows that the majority of the points closely align with the straight standard line, with minor variations occurring close to the tails. The residuals have a relatively normal distribution. It has not much evidence of skewness or heavy-tailed behaviour since the tips are not highly curled or S-shaped. This demonstrates that there is statistical reliability in the

experimental SWR responses. SWR data fluctuation was effectively stabilised by the S/N ratio modification. Thus, the SWR response may be accurately predicted by the presented model with a satisfactory level of statistical confidence.

The residuals vs fitted plot assesses the degree to which predicted S/N ratio levels affect prediction errors. Around 0, residuals disperse at random. It has no curvature or funnel structure which demonstrates that the error variance is consistent at various SWR values. It precisely reflects the connection between SWR and process variables. There are no undefined, important nonlinear interactions. For all SWR operating circumstances, the prediction quality is consistent owing to the S/N ratio model.

The distribution of experimental SWR deviations around the predicted mean response is shown in the histogram. Around zero, residuals are mostly symmetrical. This demonstrates that the SWR prediction errors, both positive and negative, are equal. Overestimation and underestimation are not consistent. In lieu of being biased, experimental uncertainty is random. SWR variability was successfully decreased using the Taguchi S/N optimisation.

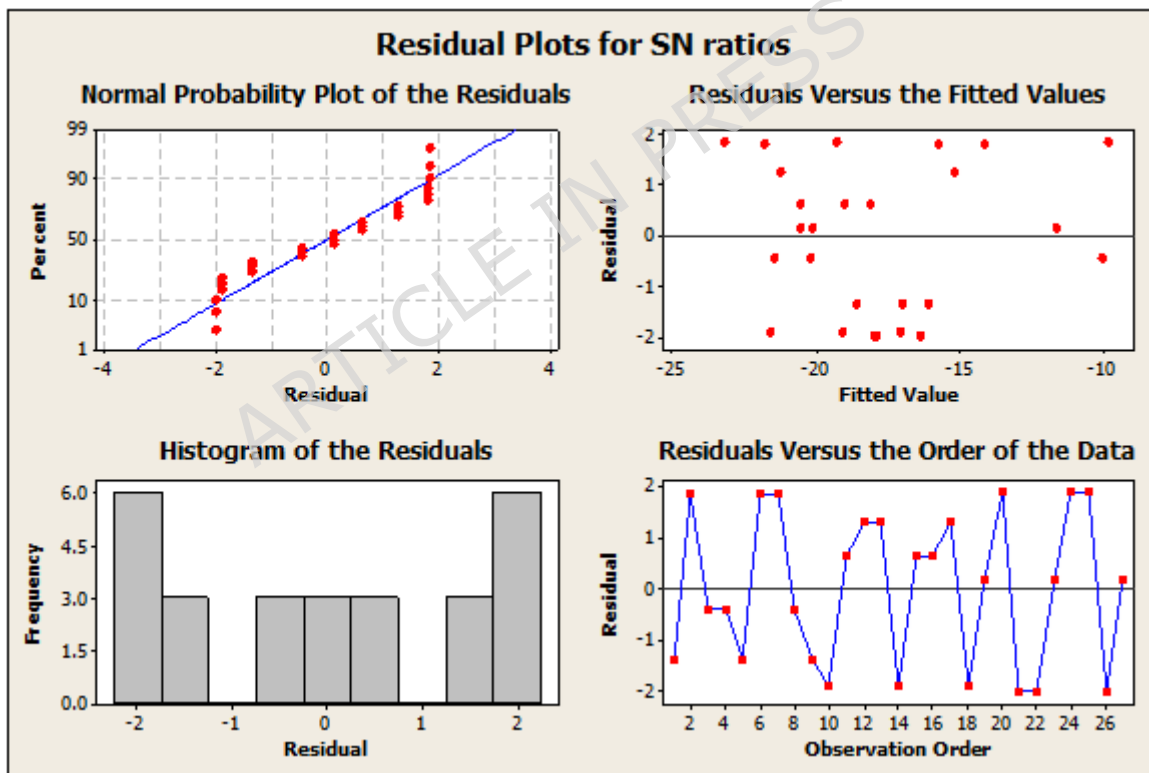


Figure 7. Residual Evaluation of S/N Ratio-Based SWR Model in Al413/B₄C Composite

SWR observations are checked for instability during experimentation using residuals versus observation order. Around 0, the residuals fluctuate at random. There isn't a steady rise or declining trend. There is an alternating pattern, although it is not really systematic.

This suggests that during SWR testing, the measuring conditions stayed constant. There was no increasing deviation, instrument instability, or thermal drift.

3.3.3 Identification of Optimal Levels for SWR and ANOVA of responses

For each level of each factor, the mean of each output characteristic is displayed in Table 6. The magnitudes of the effects are compared in the table using ranks. The rank shows the relative significance of each component to the output. SWR is most affected by load, followed by 'D', 'R', and 'S' in order, according to the rankings and delta values. Figure 6 displays that the optimal values are provided by the 1st 'S' level, 2nd 'D' level, 3rd 'L' level, and 3rd reinforcement level. ANOVA was implemented to analyse the effectiveness of the process variables influencing SWR. A significance level of $\alpha=0.05$, or a 95% confidence level, is used for this study. At the 5% significance level, the table's F-values are $F_{(0.05, 2, 14)} = 3.74$ and $F_{(0.05, 4, 14)} = 3.11$. Therefore, 'L' is the only significant factor, as shown in ANOVA Table 7. The F values are extremely close to both 'D' and the relationship between 'S' and 'D'. The error term was created by combining the effects of 'S' with 'L' and 'S' with reinforcement percentage.

Table 6. Statistical Response Analysis (S/N Ratio) of SWR in Al413/B₄C Composite System

Level	S (m/s)	D(m)	L (N)	R (wt %)
1	82.77	82.60	79.28	81.62
2	80.77	83.29	82.47	81.24
3	82.58	80.23	84.36	83.26
Delta	2.00	3.06	5.08	2.02
Rank	4	2	1	3

Table 7. Statistical Significance Analysis (ANOVA) of SWR in Al413/B₄C Composite System

Source of Variation	DOF	Sum of squares	Mean sum of squares	F ₀	Contribution
S	2	21.95	10.974	1.69	5.82%
D	2	46.57	23.283	3.59	12.34%
L	2	118.69	59.346	9.14	31.46%
R	2	20.76	10.382	1.60	5.50%

SD	4	78.37	19.592	3.02	20.77%
Error(Pooled)	14	90.92	6.494		24.10%
Total	26	377.26			100%

3.3.4 Confirmation Experiment for SWR

Validation tests, the last phase in the Taguchi design process, are used to confirm the study's reliability. The actual experimental mean values and the percentage error values are compared with the Taguchi-displayed mean values. The confirmation experiment is carried out, and the SWR is predicted using the ideal values. The variables at level S_1 , D_2 , L_3 , and R_3 , which are 'S' 1 m/s, 'D' 1000 m, 'L' 45 N, and R 9%, are the ideal circumstances for achieving the lowest SWR. The measured value of SWR is $4.36 \times 10^{-5} \text{ mm}^3/\text{Nm}$, while the expected value is $4.32 \times 10^{-5} \text{ mm}^3/\text{Nm}$.

3.3.5 Discussion of Results of COF

Wear tests were performed utilising L_{27} OA to investigate how wear factors affected the COF. Table 5 presents the experimental outcomes. Figure 8 displays the COF for every variable for S/N data at levels 1, 2, and 3. The COF decreases as the 'D' and 'L' decrease, and it drops as the 'S' and 'R' increase. Because there is less frictional force acting on the material due to the small 'L', the COF decreases during sliding wear as the load decreases. When it comes to COF, the sliding distance is really significant.

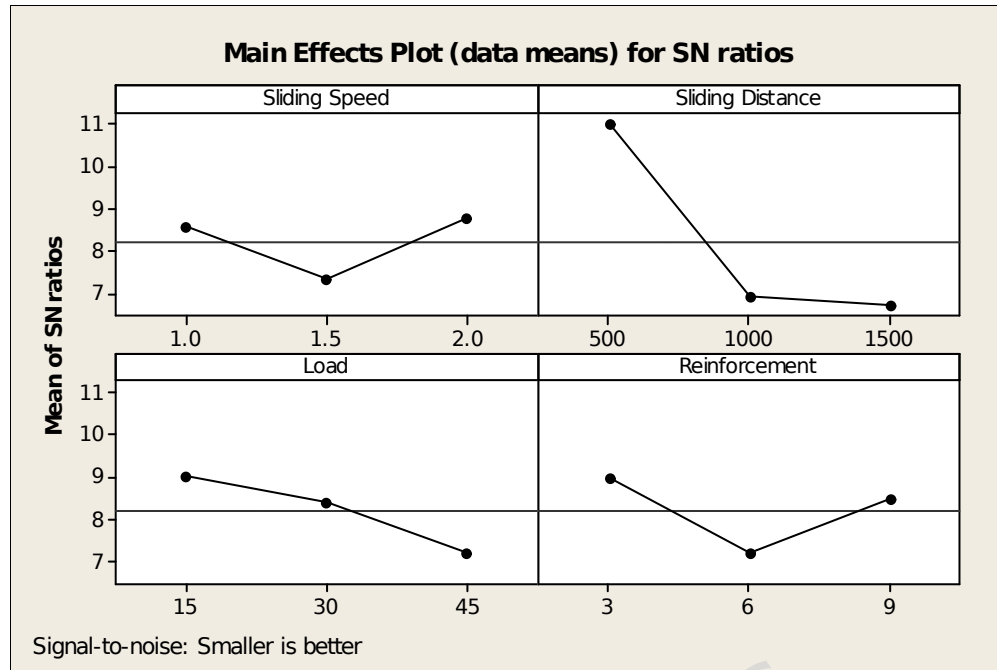


Figure 8. Graphical Representation of COF Response Behavior for Al413 Reinforced with B₄C Particles

3.3.6 Residual Plot Analysis of S/N Response

Figure 9 shows that the residual points only slightly deviate from the straight reference line at the tails. The Taguchi model effectively describes the frictional behaviour, and the near-linear distribution shows that the residual errors are roughly regularly distributed. Randomness in experiments predominates over systematic errors. These effects appear to be controlled by statistical methods and respond randomly based on the residuals' normal distribution.

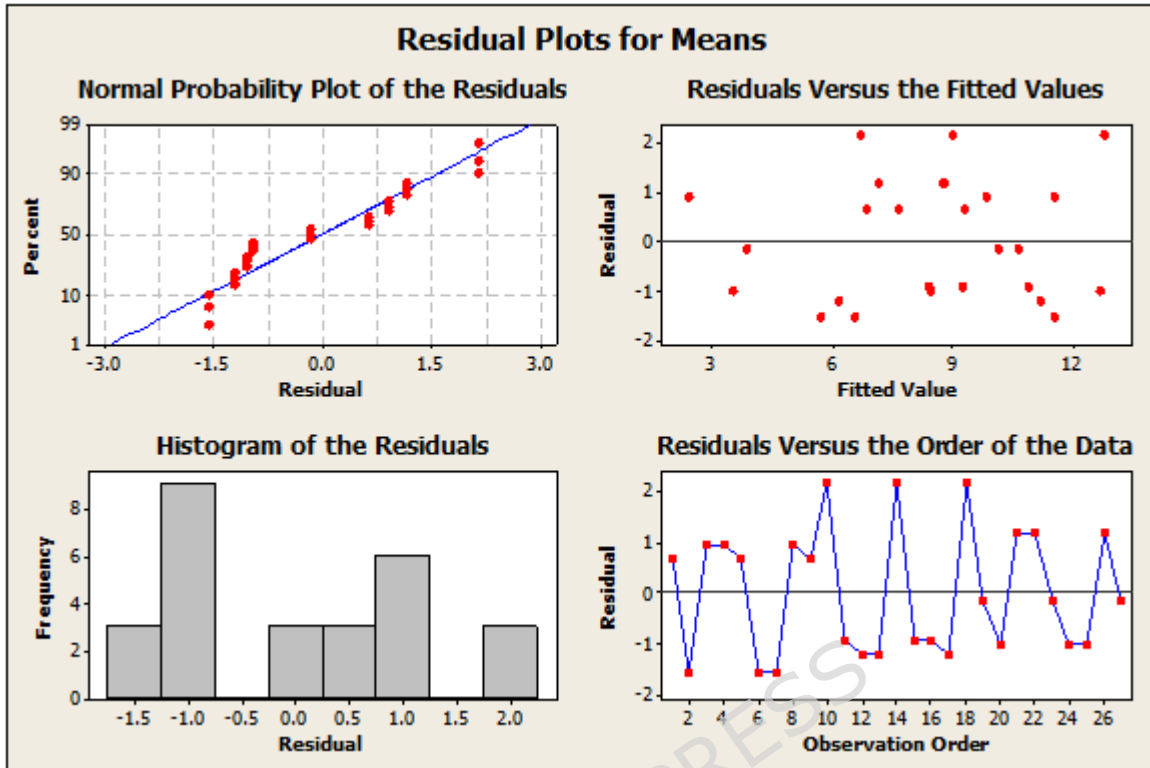


Figure 9. Residual Plot Analysis of S/N Response for Coefficient of Friction in Al413/B₄C Composite

The residuals are distributed at random about zero. It has no clustering, curvature, or funnel pattern. Under all operating conditions, the S/N ratio optimisation effectively stabilised friction behaviour. The random distribution shows that errors have a constant variance. There is no unidentified nonlinear link between COF and process variables.

The residual distribution near zero is nearly symmetrical, according to the histogram. Due to the small number of experimental runs, there is some clustering. This shows that there is a balance in the prediction mistakes. There is no consistent overestimation or underestimation of COF. There is still random variation in the experiment. The process parameters that were optimised successfully decreased COF variability and enhanced repeatability.

There is no long-term drift or cyclic tendencies in the residuals' random fluctuations. The independence of experimental findings is confirmed by this plot. Neither progressive tool or material degradation throughout trials is indicated by the lack of consistent patterns. Since there are no such patterns, accurate variable optimisation rather than experimental distortions is responsible for the observed COF gains.

3.3.7 Selection of Optimal Levels for COF

The average of each response parameter for every factor level is shown in Table 6. Minitab assigns ranks: 1 denotes the greatest delta value, 2 the second-highest, and so forth. The ranks show the relative significance of each component to the output. 'D' has the most impact on COF, followed by load, reinforcement, and 'S' in that order, according to the rankings and delta values. Figure 8 illustrates that the optimal values are provided by the 1st level of 'L', the 1st level of 'D', the 3rd level of 'S', and the first level of R %. ANOVA was used to examine the significance of the process variables for COF. At the 5% significance level, the table's F-values are $F_{(0.05,2,8)} = 4.46$ and $F_{(0.05,4,8)} = 3.84$. 'D' is therefore found to be the most significant factor in ANOVA Table 9.

Table 8. Response Table for Optimization of COF in Al413/B₄C Tribological System

Level	Sliding Speed, S (m/s)	Sliding Distance, D(m)	Load, L (N)	Reinforcement, R (wt %)
1	8.57	11.02	9.04	8.99
2	7.32	6.93	8.41	7.21
3	8.78	6.73	7.23	8.48
Delta	1.46	4.29	1.81	1.78
Rank	4	1	2	3

Table 9. Statistical Significance Analysis (ANOVA) of Coefficient of Friction (COF)

Source of Variation	DOF	Sum of squares	Mean sum of squares	F0	Contribution
D	2	105.65	52.83	13.61	38.09%
L	2	15.13	7.57	1.95	5.46%
R	2	15.18	7.59	1.96	5.47%
DL	4	34.43	8.61	2.22	12.41%
DR	4	33.67	8.42	2.17	12.14%
LR	4	42.25	10.56	2.72	15.23%
Error (Pooled)	8	31.03	3.88		11.19%
Total	26	277.34			100%

3.3.8 Confirmation Experiment for COF

To determine the ideal parameters, experimental data are examined. The ideal parameters for achieving the lowest COF are determined by Figure 8, response Table 8, and the factors at levels S_3 , D_1 , L_1 , and R_1 : 'S' of 2 m/s, 'D' of 500 m, load of 15 N, and 3% reinforcement. The experimental and expected values of COF are 0.245 and 0.258, respectively.

3.4 MICROGRAPHS OF WORN PINS

The SEM images of worn aluminium alloy (413) pins and their composites with lower wear rates, showing the right parameters, are shown in Figure 10. SEM images of the worn pins in 413 Al alloy are shown in Figure 10a. The existence of debris from wear suggests that the irregularities were sheared by adhesive and plastic during the wear test [53]. One of the most frequent problems with components is adhesive wear, which happens when there is excessive contact stress between two contact surfaces. Wear-resistant and heat-resistant materials can be used to stop adhesive wear. The images of the worn surface of the Al 413 alloy show wider patches and smaller grooves in the sliding direction. These indicate more extensive wear and localised adherence between the pin's surface and the disc, which is probably due to heat generated by friction, leading to the formation of oxide layers. The SEM images of 413 + 9% B_4C are shown in Figure 10b. Wear on the counter face is increased by the reinforcements' abrasive action. When two surfaces are in contact with each other, atoms across the surfaces can form covalent bond and these bonded regions are called as junction. During the action of sliding, shear stress develops where material is removed from one surface and transferred to the other. Even smooth surfaces also considered as rough at microscopic level. Higher adhesion leads to high friction and material transfer.

Furthermore, reinforcement is released as wear debris abrasively contacts the composite and counter face [54]. Particles are susceptible to ploughing because they are weaker and smaller than B_4C . Consequently, a lower wear rate is observed compared to virgin 413 alloys. The boron carbide particles at the interface contributed to the decreased wear rate and friction. Oxide layers and plastic deformation are visible on the worn surface. Oxides are created on the workpiece's surface when oxygen is present in the surrounding air. Wear rates are decreased by even minute amounts of oxygen. Accordingly, oxidative wear is only advantageous during the grinding process. On the other hand, wear rates might be higher when oxygen creates hard oxides. The breaking of the oxide layers is clearly seen in the SEM image. The shift in wear strategy from extreme to moderate wear can also due to increased reinforcing content. According to Rao et al., the strong reinforcement in an Al matrix leads to less severe plastic deformation. It is seen that the hard dispersoids improved the hardness, increasing WR. The specimen and counter face have extremely little contact time as speed increases, resulting in less material removal.

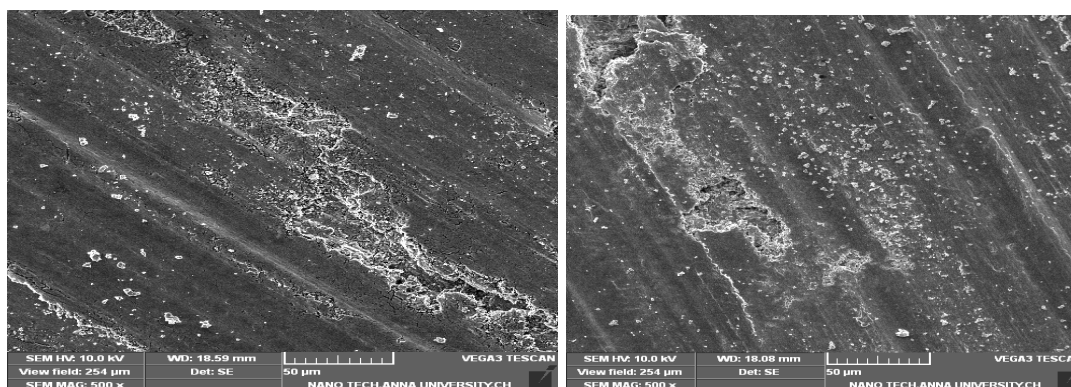


Figure 10. Surface Morphology of the Worn Pin in Al413/B₄C Composite System of a, 413 alloy b, 413 + 9% B₄C

Figure 11 (EDS) displays the fundamental composition of LM413/B₄C. The highest peak indicates a high concentration of aluminium and traces of all other elements. Despite being physically present in the composite, boron from the B₄C reinforcement frequently seems to "disappear." Because of oxide layers, air in the chamber passage, and surface contaminants all strongly absorb the extremely low-energy X-rays that boron emits. Further, heavier elements (Al, Si, Fe, Cu, Zn, etc.) are significantly easier to identify using SEM-EDS systems. Sometimes carbon and boron are close to the lower detection limit. The boron peak could decrease below the noise level if the B₄C proportion is low.

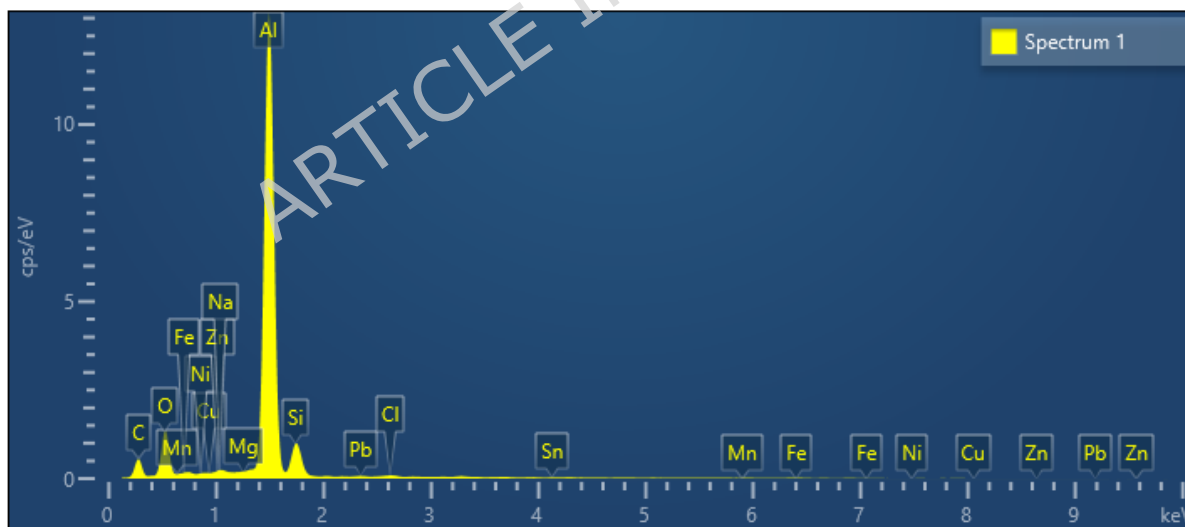


Figure 11. EDS Spectrum Showing Elemental Distribution in LM413/B₄C Composite System

3.5. X-Ray Diffraction Study for Phase Composition of Al413/B₄C Composite

Figure 12 shows the XRD pattern of the prepared 413/B₄C composite. Bragg's law states that the peaks result from the constructive interference of X-rays scattered by crystal planes. Aluminium is the predominant crystalline phase, as indicated by the prominent peaks seen

at 38.4° , 44° , and 65.26° , which correspond to the (h k l) plane ((113), (200), (220)). The existence of boron carbide is confirmed by peaks marked at 21.42° (0 0 3), 56.3° (2 0 3), and 65.26° (2 2 0), which are typical of B_4C . The Al (113) peak's extremely high intensity indicates to a significant volume fraction of Al. In comparison to Al, Si peaks are weaker (at 28.4° & 47.34°), suggesting a smaller proportion or lower crystallinity. B_4C peaks are present, but their strength is comparatively modest, revealing a small reinforcing phase. High crystallinity is indicated by peak sharpness; low micro strain and relatively large crystallite size are implied by no apparent widening. Minimal amorphous material is suggested by the low, slowly changing background. The pattern demonstrates a composite material with scattered boron carbide phases in an aluminium matrix. The results presented in the figure 12 are in well consistent with the existing literature [55,56].

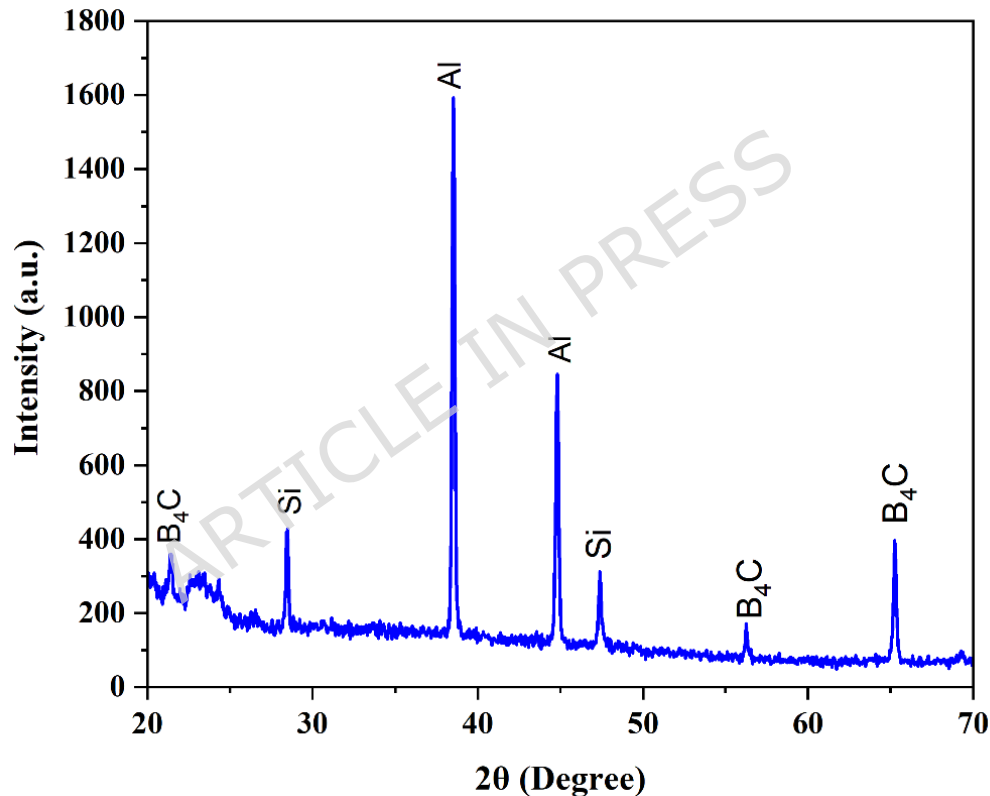


Figure 12. X-ray Diffraction Characterization of LM413/ B_4C Metal Matrix Composite

4. Discussion

4.1 Impact of Process Variables on SWR

4.1.1 Influence of 'S' as a function of SWR

The primary consideration is disc speed, which may be due to the simple fact that the temperature in the contact region quickly rises as disc speed rises. The material's strength

will decrease due to this temperature increase, as the atoms' bonds will weaken more rapidly. As the operation duration increases, the interaction duration between the specimen and the disc increases correspondingly, raising the temperature at the point of contact and causing the sample to wear quickly [57]. It is observed that raising 'S' lowers the WR and COF. It is hypothesised that the transfer layer on MMC acts as a protective layer, delaying wear and decreasing friction. The competing effects lead the WR to decline as S is increased at low speeds. It is well understood that the hardness of a material is determined by how rapidly it can be indented. Friction heats the material, causing it to soften, which is another key effect of raising S. Figure 13 depicts the impact of sliding speed on SWR.

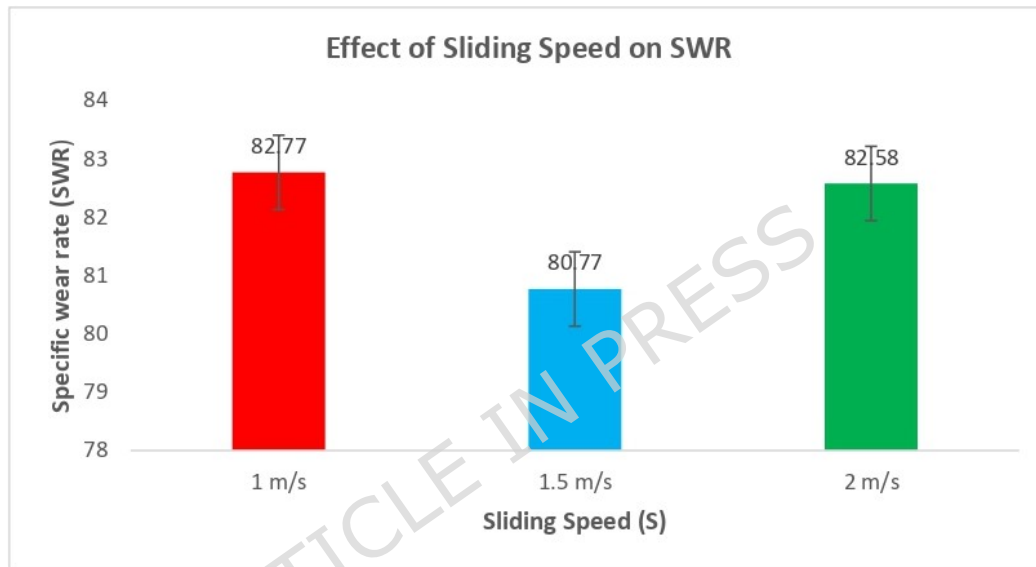


Figure 13. Influence of Sliding Speed on SWR in Al413 Reinforced with B₄C Particles

4.1.2 Impact of 'D' on SWR

The 'D' rises as the SWR increases. As the 'D' increases, so does the volume loss due to wear. This may be because raising the 'D' does not diminish the potential of the shattered particles trapped between the counter face and the pin to cut. Adhesive wear is more common in unreinforced alloys than abrasive wear in composites. Despite increasing stresses, the main mechanism in both alloys and composites is subsurface separation [58]. However, the decrease in SWR is seen in the Figure 14 at the highest 'D' of 1500 m is observed. This may be because the oxide layer formed during sliding is stable at a certain 'D' value, leading to lower SWR. At longer 'D', the debris formed between the surfaces may act as a lubricant, reducing SWR.

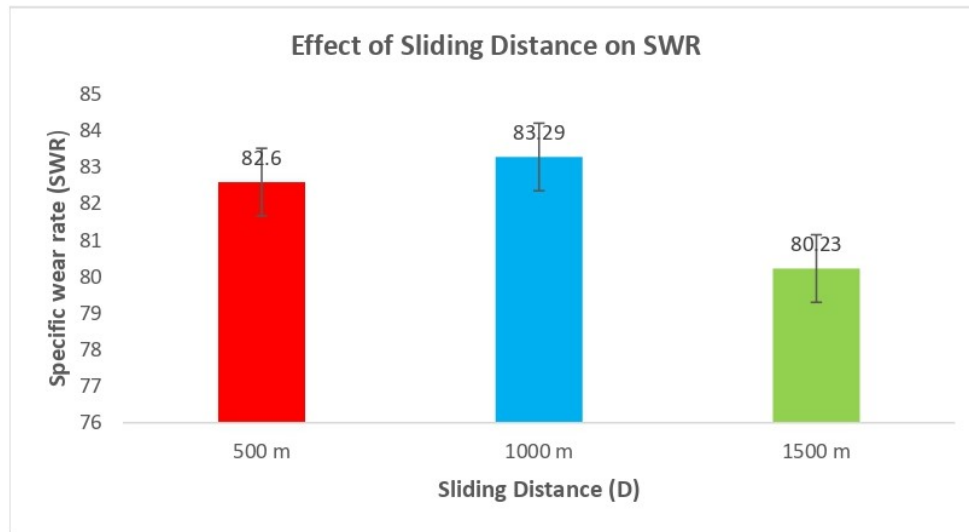


Figure 14. Influence of Sliding Distance on SWR in Al413 Reinforced with B₄C Particles

4.1.3 Effect of Load on SWR

As the specimen's weight develops, it also raises the contact pressure between the disc and the specimen, resulting in increased wear. The material will stick to the disc surface because it is removed as a powder, which minimises the new surface contact between the disc and the sample. As the track diameter increases, less powder is collected in the contact zone, allowing the fresher portion of the disc to reach the specimen, resulting in increased wear [59]. At peak levels and over time, the sliding process occurs in tiny areas. Ruptures at peaks increase the contact area, raising the temperature. Friction increases as the load increases. These results are consistent with those of Kallesh and Marigoudar [60] for aluminium, as well as for surfaces that include (i) moisture, (ii) metal oxide, and so on. During the initial rubbing period, the aluminum-silicon casting alloy readily oxidizes in air. The metal deteriorates and wears down more when the load increases. In addition to cleaning and smoothing the surfaces, the initial rubbing time strengthens the bonds and contact between the surfaces by breaking down the surface layers—the surface temperature increases due to tillage-induced friction. Adhesion and increased displacement at the surface layers are outcomes of this process, leading to greater metal loss. This outcome aligns with the findings of Miroslav and Slobodan [61]. The steel disc's abrasive action is another factor contributing to composite wear. Pits were left behind when B₄C was removed from the surface during the test. The specimen's material begins to deteriorate due to abrasion. On the surface of the material, scratches first appear at lesser loads. As 'L' increases, these scratches transform into deep grooves that run along the steel disc's rotational path. Subsurface fracture

propagation is the cause of this groove creation [62]. As load, abrasion, and pressure increased, the SWR of the AMCs increased accordingly. The substance is removed from the pin's surface by three-body abrasion from tiny, fractured ceramic particles. As the stress increases, larger broken particles develop and pass through the pin. There has been increasing wear as the typical load has increased. Several researchers have written about how load affects SWR. All of these tests demonstrated that the rate of MMC wear increased in accordance with the increase in the rise in applied force.

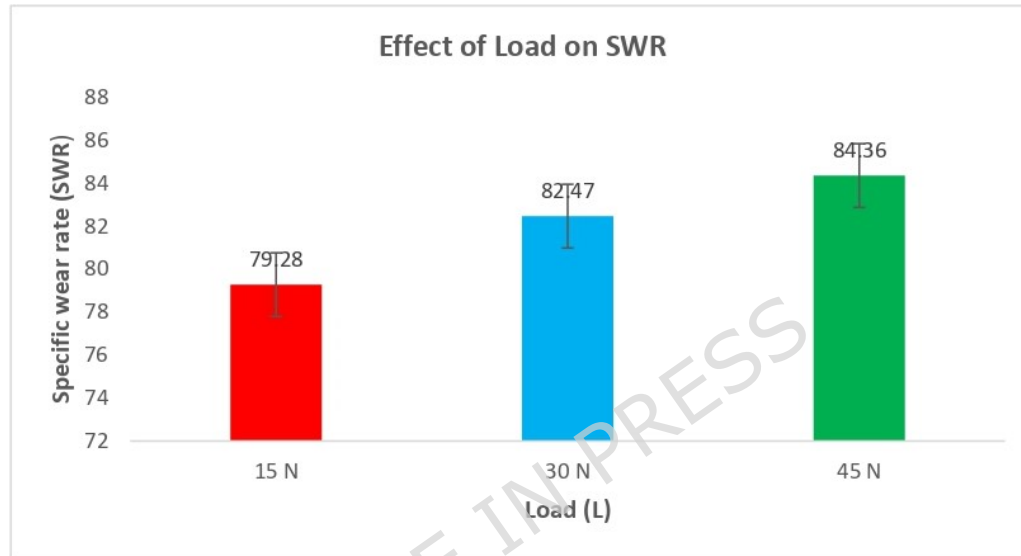


Figure 15. Influence of Applied Load on SWR in Al413 Reinforced with B₄C Particles

4.1.4 Effect of Reinforcement Percentage on SWR

According to the findings, MMC with less reinforcement exhibits superior performance compared to MMC with different components. Compared with MMC with a higher reinforcement level, MMC with a lower reinforcement content experienced less volume loss. During the wear test, the bond between the B₄C and the matrix will prevent the composite from delaminating. Hardness rises with increasing reinforcing content. The Physics behind the increase in SWR with an increase in dispersoid is that a high dispersoid percentage may cluster and form a weak zone. These clusters break off easily, which can generate substantial wear debris and high SWR. The bonding between the matrix and dispersoid may be weakened, so that the particles can be easily removed during sliding, which causes high SWR. The addition of a large quantity of dispersoid can form a brittle composite material. The composite's brittle nature also increases the SWR. The inference from this analysis is that the presence of dispersoids can enhance properties, such as

hardness, up to a threshold value. The threshold value of the B_4C is greater than 15%. Below this threshold value, load transfer property and interfacial bonding between the continuous phase and the dispersoid will be effective. At the threshold value, particles start agglomerate which can produce weak zones and makes the composites less ductile. The interfacial bonding between the matrix and B_4C are poor so that the particles can be easily detached during wear. Beyond the threshold value, an increase in dispersoid content may cause clustering, which decreases bonding among the dispersoid and continuous phase and makes the composite brittle. After further increases in the reinforcing material, the gain in wear resistance will decrease. Figure 16 shows the effect of 'R' on SWR.

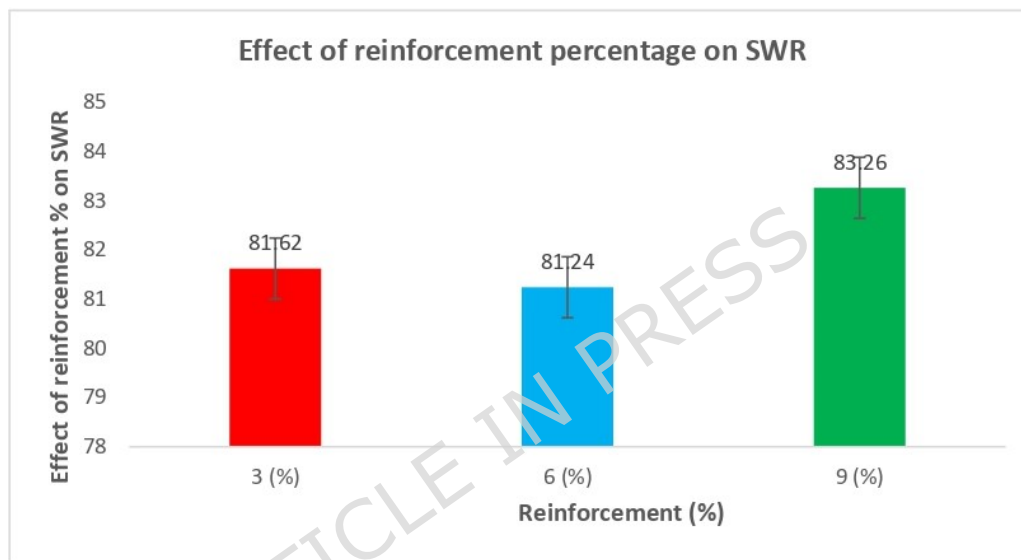


Figure 16. Influence of B_4C Reinforcement Percentage on SWR in Al413 Matrix Composite

4.2 Impact of Process Variables on COF

4.2.1 Impact of Sliding Speed on COF

Higher sliding velocities have been found to reduce both MMCs' COF and wear rate. The dispersed layer on MMC is expected to act as a protective layer, simultaneously decreasing the wear rate and COF. As the 'S' increases, the wear rate decreases [63]. As 'S' increases, the amount of strain will also increase, increasing hardness. This increase in hardness will decrease the wear rate by reducing the true area of contact. A further major effect of raising 'S' is the increase in temperature caused by frictional heat, which softens the substance being used. The increased real area of contact will therefore result in a higher wear rate [64,65].

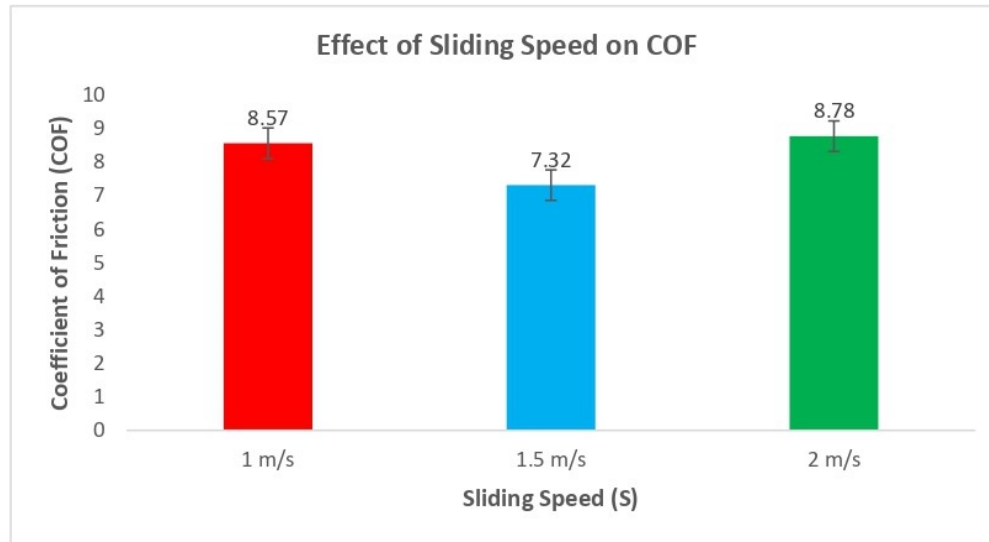


Figure 17. Influence of Sliding Speed on COF in Al413 Reinforced with B₄C Particles

4.2.2 Effect of Sliding Distance on COF

It is noted that the layer of the pin on the disc causes the average COF to be significantly high at the beginning of the rubbing motion. For short 'D', the average COF is high, while for higher 'D', it steadily decreases [66]. As the wear progressed, abrasion smoothed the rough surfaces of the Al alloy and its composite, forming a layer at both the composite specimen's and its counterpart's interfaces. Consequently, after the constant-wear stage is reached, reduced friction coefficients are achieved. The decrease in COF with a rise in 'D' is due to the formation of debris between the surfaces. This acts as a 'buffer', reducing contact between the surfaces, or the debris may act as a lubricant, decreasing COF. In some cases, the wear may form a smoother, less roughened surface, leading to a reduction in COF. When the two surfaces slide against each other, friction generates heat. An increase in temperature may cause the material to soften, reducing the COF.

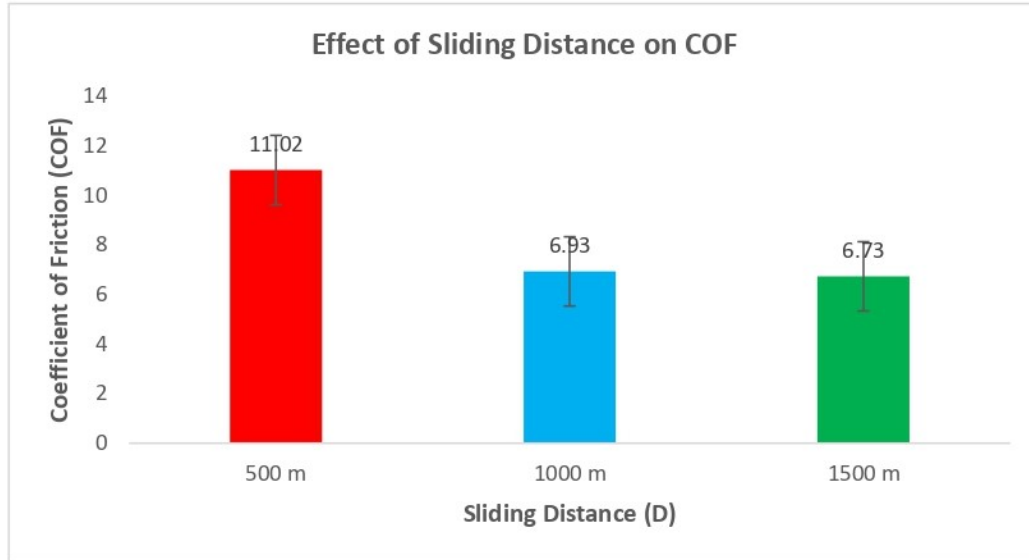


Figure 18. Influence of Sliding Distance on COF in Al413 Reinforced with B₄C Particles

4.2.3 Effect of Load on COF

The contact area between the pin and disc increased with increasing stress, and, as a result, COF decreased [67]. The enhanced COF is caused by frictional heating at countersurfaces under higher stress conditions. As 'L' and 'S' increase as a result of the shift in shear rate, the COF decreases. This phenomenon alters the mechanical characteristics of materials, causes surface wear and degradation, reduces the contact area, and fractures the oxide layer, all of which contribute to adhesion. From figure 19, COF decreases with increasing load increases, microscopic surface imperfections undergo deformation, either plastic or elastic, which increases the real area of contact. Such microscopic variations may flatten out and increase contact area, thereby reducing COF.

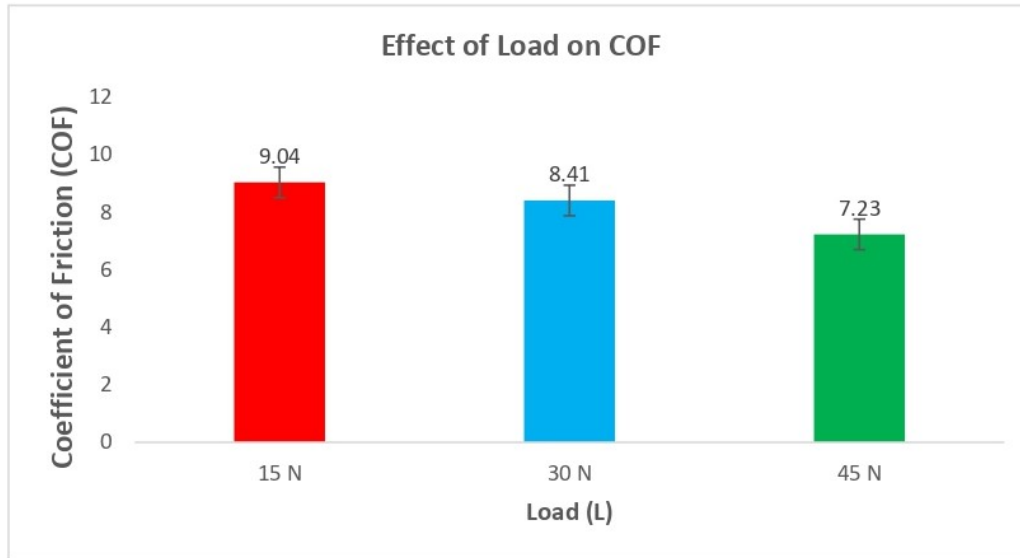


Figure 19. Influence of Applied Load on COF in Al413 Reinforced with B₄C Particles

4.2.4 Effect of reinforcement percentage on COF

Figure 20 illustrates how adding dispersoid lowers the average COF. This could occur due to the B₄C/Al matrix reinforcement, which reduces the tangential force acting on the composite pin as it slides continuously [68]. Furthermore, due to their improved dispersion of fine particles and interfacial bonding, composites with a higher B₄C content in the dispersoid mixture exhibited lower wear rates. Numerous investigations have found that the more reinforcing material used, the greater the dry slide wear resistance. Further increases in reinforcing material will decrease the gain in wear resistance.

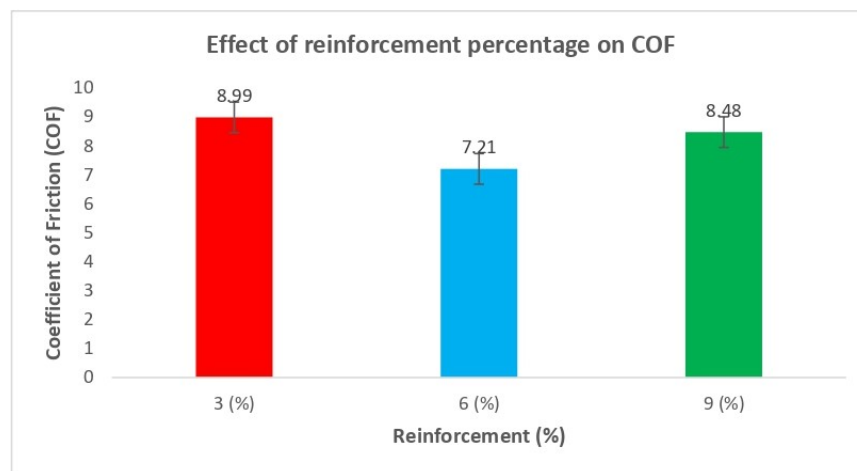


Figure 20. Influence of B₄C Reinforcement Percentage on COF in Al413 Matrix Composite

Thus, the results verify that high 'L' and 'S' are the causes of the rise in wear rate. Furthermore, sliding over extended distances reduces wear and hardens the surface layer of waste debris. The increasing load during the testing is what causes the rise in volumetric wear, wear rate, and roughness. These results are consistent with those of Chelladurai et al [69], who demonstrated that plastic flow along sliding surfaces increases the true area of contact, thereby increasing the frictional force and the spatial connections. The projections gradually flatten as the surface temperature rises, leading to a steady state and increasing the sliding speed at higher temperatures. This lowers the COF, shear force, and roughness. The strength of materials decreases as the normal 'L' increases because frictional heat is produced at the surface of contact [70].

5. Mathematical Model

The statistical application "MINITAB 18" generated a regression model that shows the relationship between the two distinct response parameters. To ascertain the relationship between a distinct or predicted variable and a response variable, this model fits an equation to the observed data. The most significant variables obtained from the ANOVA study, the "S," "D," "L," and "R" percentages, were shown to be related in the resulting regression formula.

The regression equations for the specific wear rate and COF are given in equation 5.1 and 5.2.

$$\text{SWR} = 11.8 + 0.29 S + 0.00169 D - 0.140 L - 0.199 R\% \text{ Eq (5.1)}$$

$$\text{COF} = 0.256 - 0.0234 S + 0.000156 D + 0.00140 L - 0.00156 R\% \text{ Eq (5.2)}$$

5.1 Residual Plots for regression - SWR

The normal probability plot shows that the residual points closely follow the straight reference line, with minor deviations near the tails. This indicates that the residuals have a relatively normal distribution. Thus, there is a satisfactory fulfilment of the regression assumption of normality.

As a result, the fundamental assumptions of linear regression are mostly fulfilled. There may still be some moderate non-normality, but not enough to render the model invalid.

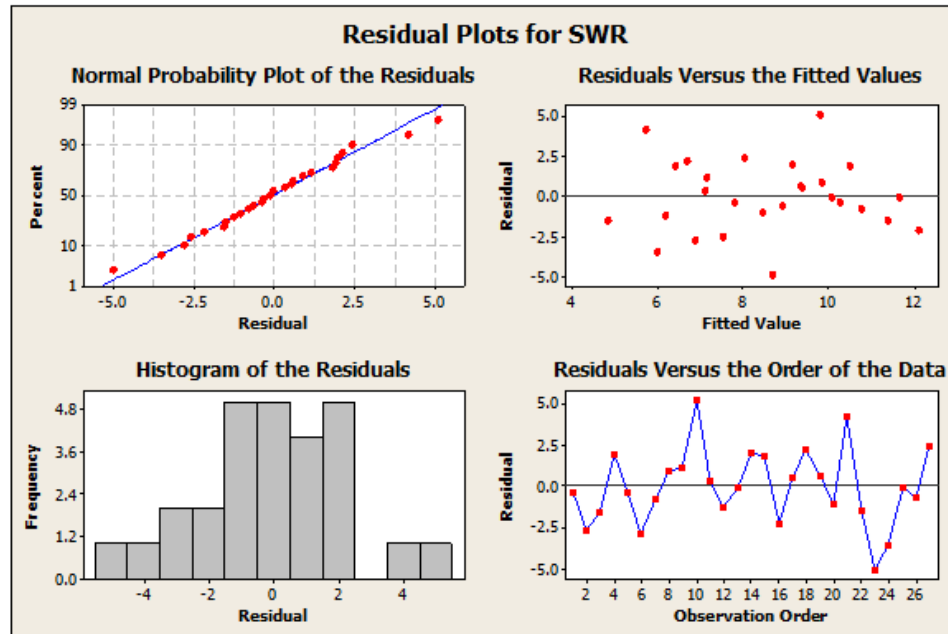


Figure 21. Residual Plot Analysis for Regression-Based Prediction of Specific Wear Rate (SWR)

5.2 Residual Plots for regression - COF

Since the residuals are essentially normally distributed, the residual diagnostics show that the regression model for COF is statistically sufficient. For prediction, optimisation, and statistical inference pertaining to COF, the regression model is therefore statistically reliable. Even though there can be some degree of skewness, the regression model's validity is not greatly impacted by these deviations.

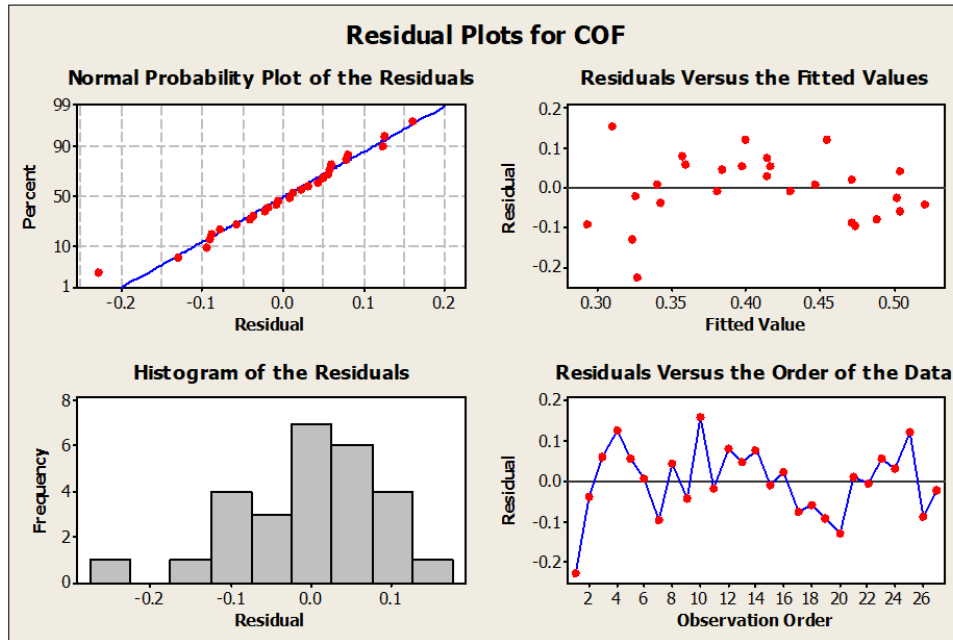


Figure 22. Residual Plot Analysis for Regression-Based Prediction of Coefficient of Friction (COF)

5.3 Error analysis between Experimental and predicted values of SWR & COF

To assess the designed regression model's predictive power, dependability, and adequateness, error analysis is crucial. The model prediction and experimental evidence match better when the error magnitude is smaller.

5.3.1 Interpretation of SWR Errors

The predicted and experimental SWR values closely align in a number of trials. This suggests that the relationship between sliding speed, load, reinforcement content, and wear behaviour was effectively represented by the regression model.

Because of wear behaviour is intrinsically complicated and unpredictable, errors between ± 5 and 25% are frequently observed in tribological tests. In many wear researches, these variations are accepted by the scientific community. There are significant variances ($>50\%$) in certain studies. The development of abrasive particles, oxidation, delamination, adhesion, and the change from mild to severe wear are all common wear processes.

It is challenging to depict these systems with simple regression equations. These changes make SWR extremely nonlinear and challenging to predict with certainty.

Table 10. Comparative Error Analysis Between Experimental and Predicted SWR and COF Values

Exp. No.	S (m/s)	D(m)	L (N)	R (wt %)	Experimented SWR	Predicted SWR	Error %	Experimented COF	Predicted COF	Error %
1	1	500	15	3	9.92	10.24	-3%	0.098	0.327	23%
2	1	500	30	6	4.98	7.54	-51%	0.305	0.343	-11%
3	1	500	45	9	3.33	4.84	-45%	0.418	0.360	16%
4	1	1000	15	6	12.46	10.49	16%	0.524	0.400	23%
5	1	1000	30	9	7.48	7.79	-4%	0.472	0.417	13%
6	1	1000	45	3	4.13	6.88	-67%	0.455	0.447	2%
7	1	1500	15	9	9.98	10.73	-8%	0.378	0.474	-26%
8	1	1500	30	3	10.75	9.83	9%	0.547	0.504	8%
9	1	1500	45	6	8.3	7.13	14%	0.478	0.520	-9%
10	1.5	500	15	6	14.95	9.79	35%	0.469	0.311	35%
11	1.5	500	30	9	7.48	7.09	5%	0.307	0.327	-6%
12	1.5	500	45	3	4.96	6.18	-25%	0.437	0.357	22%
13	1.5	1000	15	9	9.98	10.03	-1%	0.433	0.384	13%
14	1.5	1000	30	3	11.16	9.13	18%	0.491	0.414	19%
15	1.5	1000	45	6	8.3	6.43	23%	0.421	0.431	-2%
16	1.5	1500	15	3	9.92	12.07	-22%	0.493	0.471	5%
17	1.5	1500	30	6	9.96	9.38	6%	0.41	0.488	-19%
18	1.5	1500	45	9	8.87	6.68	25%	0.446	0.504	-12%
19	2	500	15	9	9.98	9.33	6%	0.204	0.294	-44%
20	2	500	30	3	7.44	8.43	-13%	0.195	0.325	-66%
21	2	500	45	6	9.96	5.73	42%	0.352	0.341	3%
22	2	1000	15	3	9.92	11.37	-15%	0.375	0.382	-2%
23	2	1000	30	6	3.74	8.68	-132%	0.455	0.398	14%
24	2	1000	45	9	2.49	5.98	-140%	0.445	0.414	7%
25	2	1500	15	6	11.63	11.62	0%	0.578	0.455	27%
26	2	1500	30	9	8.32	8.92	-7%	0.382	0.471	-23%
27	2	1500	45	3	10.47	8.02	23%	0.478	0.502	-5%

5.3.2 Interpretation of COF Errors

As friction is typically more stable under steady sliding conditions and less sensitive to abrupt material removal, COF prediction methods exhibit somewhat lower variability than SWR. This suggests that frictional performance is better represented by the regression model than wear behaviour. A large percentage of COF errors remain within $\pm 25\%$, which is a reasonable level of prediction accuracy. This demonstrates that the chosen process variables have a significant impact on COF and that friction mechanisms are accurately predicted.

As a result, the model's reliability with experimental values is comparatively better. The majority of predicted error occurrences stay within an engineering range that is permissible. The COF model is statistically more reliable and dependable than the SWR model, according to residual analysis and error trends. The trends in tribological behaviour of SWR and COF are accurately predicted by the developed regression models. On the other hand, SWR prediction methods are more impacted by complicated nonlinear wear phenomena and experimental uncertainties, while COF predictions show reduced variability and superior statistical reliability.

6. Conclusions

The primary objective of this work is to create 413/B₄C composites and to determine the optimal set of variables and factors that influence their wear behaviour.

- Using the stir-casting technique, 413/B₄C composite was successfully produced by mixing varying amounts of boron carbide (3, 6, and 9 wt. %).
- Optical microscope images have verified the uniform dispersoid dispersion in the continuous phase.
- According to the S/N ratio and mean response table, the ideal variables for the enhanced wear behaviour were determined to be 1 m/s for 'S', 1000 m for 'D', 45 N for 'L', and 9% reinforcement.
- It was found that when the load increased, SWR increased.
- The ANOVA revealed that load is the most significant factor, accounting for 31.46% of the total, followed by the interaction between 'D' and 'S' (20.77%), and finally, 'D' (12.34%).
- The SWR was effectively realised by developing a regression model.
- MMC with less reinforcement exhibits superior performance compared to MMC with different components.
- The mathematical model systematically accounted for the impact of the wear variables on the specific wear rate and COF.

Numerous variations on combinations and optimisation techniques may be used in the future. The wear resistance and COF can be improved through further investigations into the optimal concentration and combination of reinforcing elements. In general, this study contributes to the field of materials science and engineering by improving our comprehension of friction and wear behaviour in composites and establishing a basis for their practical application in a variety of engineering applications. The study's conclusions have important consequences for a number of industries, including biomedical engineering, aircraft, and the automobile sector.

The outcome of this study has important significance for industries that need materials with improved wear resistance, such as brake pads and bearings. The resulting composites are also useful in electrical applications, including sliding conductive contacts, where conductivity and endurance depend on wear resistance. The full potential of Al/B₄C composites will be revealed by further investigation on optimising B₄C particle size (micro to nano), corrosion resistance, life cycle, and cost analysis, rendering them a flexible choice for a variety of wear-critical industrial challenges.

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References

1. ASM Handbook, Composites, ASM International, Detroit, MI, USA, 1991.
2. Sahu, A., Ghosh, S. and Aravindan, S., Tribological Performance Evaluation of Multifunctional ZrN Coating Using Prosthetic Bio-tribometer for Load-bearing Implants Application. *Wear*, p.206684, 2026.
3. Shabana, S., Shafeeq, M.A., Jajimoggala, S. et al. Evaluation of Mechanical, Tribological, and Corrosion Properties of AA6083 with Zirconia Addition. *J Bio TriboCorros* 11, 53 (2025).
4. Hutchings, I.; Shipway, P. 6—Wear by hard particles. In *Tribology*, 2nd ed.; Hutchings, I., Shipway, P., Eds.; ButterworthHeinemann: Oxford, UK, pp. 165–236, 2017.
5. Usca, Ü.A., Şap, S., Uzun, M. and Değirmenci, Ü., Determination of mechanical and tribological properties of vacuum sintered hybrid reinforced Al-4Cu composites. *Journal of Composite Materials*, 58(26),
6. J. Kukutschov’a, et al., Wear mechanism in automotive brake materials, wear debris and its potential environmental impact, *Wear* 267 (5), 807–817, 2009.
7. Y.-F. Xing, Y.-H. Xu, M.-H. Shi, Y.-X. Lian, The impact of PM2.5 on the human respiratory system, *J. Thorac. Dis.* 8 (No 1) 2016.

8. S. Balakrishna, S. Lomnicki, K.M. McAvey, R.B. Cole, B. Dellinger, S.A. Cormier, Environmentally persistent free radicals amplify ultrafine particle mediated cellular oxidative stress and cytotoxicity, Part. FibreToxicol. 6 (1), 11, 2009.
9. P. Peikertová, et al., Water suspended nanosized particles released from nonairborne brake wear debris, Wear 306 (1), 89–96, 2013.
10. G. Straffelini, R. Ciudin, A. Ciotti, S. Gialanella, Present knowledge and perspectives on the role of copper in brake materials and related environmental issues: a critical assessment, Environmental Pollution 207, 211–219, 2015.
11. Holmberg, K., Kivikyto-Reponen, " P., H" arkisaari, P., Valtonen, K., Erdemir, A., Global energy consumption due to friction and wear in the mining industry. Tribol. Int. 115, 116–139, 2017.
12. Chen, W., Biswas, S., Roberts, A., O'Shea, J., Williams, K., Abrasion wear resistance of wall lining materials in bins and chutes during iron ore mining. Int. J. Miner. Process. 167, 42–48, 2017.
13. Garcia, J., Cipres, V.C., Blomqvist, A., Kaplan, B., Cemented carbide microstructures: a review. Int. J. Refract Metal Hard Mater. 80, 40–68, 2019.
14. Broeckmann, C., Hofter, " A., Packeisen, A., Cladding of briquetting tools by hot isostatic pressing for wear resistance. Powder Metall. 44 (5), 49–56, 2008.
15. Kivikyto-Reponen, " P., Ala-Kleme, S., Hellman, J., Liimatainen, J., Hannula, S.P., The correlation of material characteristics and wear in a laboratory scale cone crusher. Wear 267 (1–4), 568–575, 2009.
16. Sardar, S., Karmakar, S.K., Das, D., Experimental investigation on two-body abrasion of cast aluminum-alumina composites: influence of abrasive size and reinforcement content. Journal of Tribology – Transactions of the ASME 142 (3), 2020.
17. G. Heinrich, M. Klüppel, Basic mechanisms and predictive testing of tire-road abrasion, in: Degradation of Elastomers in Practice, Experiments and Modeling, vol. 289, Advances in Polymer Science, Springer, Cham, 2022.
18. Michelin North America Inc, Michelin Truck Tire Service Manual, 2017.
19. William Amoako Kyei-Manu, Lewis B. Tunnicliffe, Charles R. Herd, Keizo Akutagawa, Radek Stoček, James J.C. Busfield, Effect of carbon black properties on cut and chip wear of natural rubber, Wear 564–565, 205673, 2025.
20. Kyei-Manu, W.A., Tunnicliffe, L.B., Herd, C.R., Akutagawa, K., Stoček, R. and Busfield, J.J., Effect of carbon black properties on cut and chip wear of natural rubber. *Wear*, 564, p.205673, 2025.

21. M.M.A. Khan, M.A.H. Mithu, N.R. Dhar, Effects of minimum quantity lubrication on turning AISI 9310 alloy steel using vegetable oil-based cutting fluid, *J. Mater. Process. Technol.* 209 (15–16), 5573–5583, 2009.
22. M.K. Gupta, M. Mia, M. Jamil, R. Singh, A.K. Singla, Q. Song, M. Sarikaya, Machinability investigations of hardened steel with biodegradable oil-based MQL spray system, *Int. J. Adv. Des. Manuf. Technol.* 108, 735–748, 2020.
23. A. Das, S.K. Patel, S.R. Das, Performance comparison of vegetable oil based nanofluids towards machinability improvement in hard turning of HSLA steel using minimum quantity lubrication, *Mechanics & Industry* 20 (5), 506, 2019.
24. A.T. Abbas, E.A. Al Bahkali, S.M. Alqahtani, E. Abdelnasser, N. Naeim, A. Elkaseer, Fundamental investigation into tool wear and surface quality in high-speed machining of Ti6Al4V alloy, *Materials* 14 (23), 7128, 2021.
25. Kazeem, R.A., Fadare, D.A., Akande, I.G., Jen, T.C., Akinlabi, S.A. and Akinlabi, E.T., Evaluation of crude watermelon oil as lubricant in cylindrical turning of AISI 1525 steel employing Taguchi and grey relational analyses techniques. *Heliyon*, 10(3), 2024.
26. S. Saxena, A.S.M. Raja, A. Arputharaj, Challenges in sustainable wet processing of textiles, *Textiles and clothing sustainability: sustainable textile chemical processes* 43–79, 2017.
27. Y. Liu, D. Xu, M. Agmell, R. M'Saoubi, A. Ahadi, J.E. Stahl, J. Zhou, Numerical and experimental investigation of tool geometry effect on residual stresses in orthogonal machining of Inconel 718, *Simulat. Model. Pract. Theor.* 106, 102187, 2021.
28. Prakash, J.U., Rubi, C.S., Palani, S., Juliyana, S.J. and Sadhana, A.D., Optimization of machining parameters in drilling of LM6/B4C/Fly ash hybrid composites. *Manufacturing Review*, 9, p.28, 2022.
29. Şap, S., Değirmenci, Ü., Usca, Ü.A. and Uzun, M., Tribological behaviors and mechanical properties of novel Al-5Cu hybrid composites under dry sliding conditions. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 238(15), pp.7690–7704, 2024.
30. Sharma SC, Girish BM, Somasheka DR, Satish BM, Kamath R. *Wear* 1999, 224, 89–94.
31. Chowdhury, M. Asaduzzaman, M. K. Khalil, D. M. Nuruzzaman, and M. L. Rahaman. "The effect of sliding speed and normal load on friction and wear property of aluminum." *International Journal of Mechanical & Mechatronics Engineering* 11, no. 1 (2011): 45–49..
32. Şap, S., Değirmenci, Ü. and Usca, Ü.A., Impact of boron nitride and silicon carbide on tribological properties of Al-3Gr-based hybrid composites. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 45(10), p.510, 2023.

33. M. Parana Kumar, K. Sad, Engineering, Bapuji "Institute of Engineering & Dry Sliding Wear" India, No. 3 2006; 12
34. Hima Gireesh. C., Durga Prasad, K. and Ramji, K. Experimental Investigation on Mechanical Properties of an Al6061 Hybrid Metal Matrix Composite. *Journal of Composites Science*, 2, 49, 2018.
35. Sahu, M.K. and Sahu, R.K. Experimental Investigation, Modeling, and Optimization of Wear Parameters of B₄C and Fly-Ash Reinforced Aluminum Hybrid Composite. *Frontiers in Physics*, 8, 219, 2020.
36. Kumar, D.R., Shanmugasundaram, B. and Mohanraj, P. Fly Ash Particle Reinforced and Mechanical Properties of AL6061 Graphite B₄C Composites. *MAT Journals*, 3, 18-28, 2017.
37. Mahendra, K.V. and Radhakrishna, K. Characterization of Stir Cast Al-Cu-(fly ash + SiC) Hybrid Metal Matrix Composites. *Journal of Composite Materials*, 44, 989-1005, 2010.
38. Gangadharappa, A.M., Kumar, M.R. and Reddappa, H.N. Mechanical Properties and Microstructural Analysis of Al6061-Red Mud. *International Journal of Materials and Metallurgical Engineering*, 9, 6061, 2015.
39. Mohanavel, V., Rajan, K., Senthil, P.V. and Arul, S. Mechanical Behaviour of Hybrid Composite (AA6351+Al₂O₃+Gr) Fabricated by Stir Casting Method. *Materialstoday: Proceedings*, 4, 3093-3101, 2017.
40. Sarada, B.N., Murthy, P.L.S. and Ugrasen, G. Hardness and Wear Characteristics of Hybrid Aluminium Metal Matrix Composites Produced by Stir Casting Technique. *Materials Today: Proceedings*, 2, 2878-2885, 2015.
41. Usca, Ü.A., Şap, S., Uzun, M., Giasin, K. and Pimenov, D.Y., Evaluation of mechanical and tribological aspect of self-lubricating Cu-6Gr composites reinforced with SiC-WC hybrid particles. *Nanomaterials*, 12(13), p.2154, 2022.
42. Kaushik, N. and Singhal, S. Optimization of Wear Properties in Aluminum Metal Matrix Composites Using Hybrid Taguchi-GRA-PCA. *International Journal of Performability Engineering*, 14, 857-870, 2018.
43. Aherwar A, Singh A, Patnaik A. Study on mechanical and wear characterization of novel Co₃O₄Cr₄Mo biomedical alloy with added nickel under dry and wet sliding conditions using Taguchi approach. *Proc Inst Mech Eng Part J Mater Des App l*, 232(7):535-54, 2018.
44. Ikubanni, P.P., Oki, M., Adeleke, A.A. and Agboola, O.O., Optimization of the tribological properties of hybrid reinforced aluminium matrix composites using Taguchi and Grey's relational analysis. *Scientific African*, 12, p.e00839, 2021.

45. Jebran M, Wani MF, Gupta R. Tribological performance evaluation of polytetrafluoroethylene composites under dry sliding and aqueous environments using taguchi approach and grey relational analysis: effect of material, test environment and load. *Polym Compos* 40(7):2863-75, 2019.
46. Roy RK. A primer on the Taguchi method. 2nd ed. Dearborn, MI: Society of Manufacturing Engineers;
47. Datta S, Bandyopadhyay A, Pal PK. Grey-based taguchi method for optimization of bead geometry in submerged arc bead-on-plate welding. *Int J AdvManufTechnol* 2008;39(11e12):1136e43, 2010.
48. VenuYarasu, Peter Jurci, Jakub Hornik, Stanislav Krum, Optimization of cryogenic treatment to improve the tribological behavior of Vanadis 6 steel using the Taguchi and grey relation approach, *Journal of Materials and Research Technology* 18: 2945-2962, 2022.
49. Shafeeq, M.A., Jajimoggala, S., Shabana, S. et al. Evaluation of Wear and Hardness Characteristics of SiC-Reinforced SS304L Fabricated by Wire Arc Additive Manufacturing Method. *J Bio TriboCorros* 12, 6 (2026).
50. Usca, Ü.A., Değirmenci, Ü. and Şap, S., Investigation the effects of sustainable cooling/lubrication conditions on the Machinability of Al-3Gr based hybrid composites. *KahramanmaraşSütçü İmam ÜniversitesiMühendislikBilimleriDergisi*, 27(3), pp.688-705, 2024.
51. J. Henseler, C.M. Ringle, R.R. Sinkovics, The use of partial least squares path modeling in international marketing, in: *New Challenges to International Marketing*, vol. 20, Emerald Group Publishing Limited, pp. 277-319, 2009.
52. Santhosh Gotagunaki, Vardhaman S. Mudakappanavar, R. Suresh, Wire electrical discharge machining characteristics of rare earth oxides reinforced AZ91D magnesium alloy hybrid composite using Taguchi-grey relational analysis approach, *Hybrid Advances* 4, 100116, 2023.
53. Radhika, N., Balaji, T. V., and Palaniappan, S. Studies on mechanical properties and tribological behaviour of LM25/SiC/Al₂O₃ composites. *J. Eng. Sci. Technol.* 10, 134-144, 2015.
54. Rao, C. S. P., Selvaraj, N., and Veeresh Kumar, G. B. Studies on mechanical and dry sliding wear of Al6061-SiC composites. *Compos. Part B* 43 (3), 1185-1191, 2012.
55. Ahmad, I., Jabeen, N. and Ahmad, W., Fabrication and characterization of boron carbide/polymethyl methacrylate composites. *Fullerenes, Nanotubes and Carbon Nanostructures*, 30(7), pp.727-734, 2022.
56. Sivaprakasam, P., Hariharan, P. and Gowri, S., Optimization of micro-WEDM process of aluminum matrix composite (A413-B4C): a response surface approach. *Materials and Manufacturing Processes*, 28(12), pp.1340-1347, 2013.

57. Ravindranath B. S., Murthy B. R. N., Ramu H. C. and Sandeep Nambiar S, Process Parameters Optimization of Pin and Disc Wear Test to Minimize the Wear Loss of General-Purpose Aluminium grades by Taguchi and Simulation through Response Surface Methodology, *Eng. Sci.*, 16, 366–373, 2021.
58. Sudarshan & Surappa, MK, 'Dry sliding wear of fly ash particle reinforced A356 Al composite', *Composite Science and Technology*, vol. 265, pp. 349-360, 2008.
59. Udaya Prakash, J., Ananth, S., Jebarose Juliyana, S., Cep, R., Khedkar, N., Salunkhe, S., Abouel Nasr, E. and Kamrani, A., Parametric optimization of wear parameters of hybrid composites (LM6/B4C/fly ash) using Taguchi technique. *Frontiers in Mechanical Engineering*, 9, p.1279481, 2023.
60. Kallesh, S.S. and Marigoudar, R.N., Taguchi Method for Tribological Excellence: Insights into Copper-Based Metal Matrix Composites. *Tribology in Industry*, 47(2), 2025.
61. B. Miroslav, M. Slobodan, N. Tribological Potential of Zinc-Aluminum Alloys Improvement Faculty Kragujevac, 31, 2009.
62. Rajaneesh N. Marigoudar and Kanakuppi Sadashivappa, Effect of reinforcement percentage on wear behavior of SiCp reinforced ZA43 alloy metal matrix composites, *Sci Eng Compos Mater* 20(4): 311–317, 2013.
63. Dzierwa, A., Stelmakh, N. and Tikanashvili, N., 2023. Application of taguchi technique to study tribological properties of roller-burnished 36CrNiMo4 steel. *Lubricants*, 11(5), p.227.
64. Abdullayev, H., Huseynzade, E. and Sable, H., 2025. A Comprehensive Review of Wear Mechanisms and Mitigation Strategies for Tribological Systems. *Tribology in Industry*, 47(2).
65. Kumar, H., 2025. Study on mechanical, tribological and fracture behaviour of n-Al₂O₃ reinforced Al7075 composites using Taguchi technique. *International Journal of Cast Metals Research*, 38(2-3), pp.109-120.
66. Rajmohan, T., Palanikumar, K., Davim, J.P. and Premnath, A.A., Modeling and optimization in tribological parameters of polyether ether ketone matrix composites using D-optimal design. *Journal of Thermoplastic Composite Materials*, 29(2), pp.161-188, 2016.
67. Nuruzzaman, D.M. and Chowdhury, M.A., Effect of normal load and sliding velocity on friction coefficient of aluminum sliding against different pin materials. *American Journal of Materials Science*, 2(1), pp.26-31, 2012.

68. Ross, N.S., Gupta, M.K. and Krolczyk, J.B., 2025. Wear analysis of coated carbide tools in sustainable machining of Al7075+ Al₂O₃+ B₄C hybrid nano-composites. *Wear*, p.206419.
69. Chelladurai, S.J.S., Arthanari, R., Selvarajan, R., Kanagaraj, R. and Angappan, P., Investigation on microstructure and tensile behaviour of stir cast LM13 aluminium alloy reinforced with copper coated short steel fibers using response surface methodology. *Transactions of the Indian Institute of Metals*, 71, pp.2221-2230, 2018.
70. Değirmenci, Ü., Mechanical and tribological behavior of a hybrid WC and Al₂O₃ reinforced Al-4Gr composite. *Materials Testing*, 65(9), pp.1416-1436, 2023.

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