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Optimization of the tribological properties of hybrid reinforced aluminium matrix composites using Taguchi and Grey's relational analysis

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ABSTRACT

The tribological properties of synthesized hybrid reinforced aluminium matrix composites (AMCs) have been optimized in this study using Taguchi and grey relational analysis (GRA), methods where a L_{16} orthogonal array was used for the experimental design. Hybrid palm kernel shell ash (0–6 wt.%) and SiC (2 wt.%) formed the reinforcements of interest, which were combined in ratios ranging between 2 and 8 wt.%. Different loads (250, 500, 750, and 1000 g) and speeds (250, 500, 750, and 1000 rpm) were used as control factors. The wear samples were produced using the double-stir casting method, while a Taber type abrasion machine was used for the wear experiments. The evaluated wear index and volume loss showed that the speed and load were better influential factors on the performance characteristics of the composites than wt.% of reinforcements. The Taguchi-Grey's relational analysis gave the optimal combination of the process parameters for both the wear index and the volume loss as $A_3B_1C_1$ (Reinforcement = 6 wt.%; Load = 250 g; Speed = 250 rpm) and $A_1B_1C_1$ (Reinforcement = 2 wt.%; Load = 250 g; Speed = 250 rpm), respectively. The predicted and experimental values at the optimum conditions were confirmed to be within the range based on the performance of the confirmation test. The utilization of Taguchi and GRA methods have significantly confirmed that the influence of speed as a factor of performance was higher than load, which in turn was a better influencing factor than wt.% of reinforcements.

Introduction

In advanced materials development, metal matrix composites (MMCs) have gained broad applications in industries such as automobile, sports and recreation, aviation, marine, and so on, due to the enhanced properties of the base metals resulting from different reinforcement inclusions. Such enhanced properties of the MMCs could include the mechanical properties and tribological properties due to the inclusion of the reinforcing materials into the metal matrix [1–4]. Monolithic and

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hybrid reinforcements have been used in the synthesis of MMCs. These have helped in the development of MMCs with different characteristics for the mechanical and tribological properties [5–8]. Halil et al. [6] utilized hybrid reinforcement of SiC and B_4C in the production of MMC using Al6061 as the base metal. The wear and mechanical properties of the produced Al MMCs were characterized without optimization of the processes. Also, the study of the hardness and wear behaviour of hybridized reinforcement composites conducted by Sarada et al. [7] using activated carbon and mica incorporated into LM25 alloy ingots considered all physical attributes without optimizing the parameters. Thus, there seems to be a shortfall in considerations using optimization techniques to maximize the use of composite materials based on Al 6063.

However, some recent studies have considered the application of various methods such as Taguchi, response surface methodology, full factorial, analysis of variance (ANOVA), in the design of experiments (DOE) during the synthesis of MMCs using either monolithic or hybrid reinforcements. These methods are useful in the provision of vital information on the different factors in hierarchical rank order [9]. The tribological behaviour of hybrid composites developed by Stojanovic et al. [9] was optimized using Taguchi's method and artificial neural network (ANN). The tribological tests were performed using the block-on-disc tribometer under lubricated sliding condition. For the optimization, the L27 orthogonal array was set with three factors (sliding speed, load, and sliding distance) and three levels for speed (0.2, 0.5, and 1 m/s) and loads (40, 80, 120 N), and one level for the sliding distance (2400 m). The results of the wear rate and coefficient of friction (COF) were analyzed using ANOVA technique at a confidence level of 95%. From the analysis, the hybrid composites containing 3 wt.% graphite (Gr) showed the least values of wear and friction. The ANN was used to predict the wear rate and COF with the coefficient of regression of 0.98905.

Al 7050 alloy was reinforced with SiC and the wear analysis was conducted using Taguchi's method. An L9 orthogonal array was used in the DOE. Three parameters and levels, such as reinforcement percentage level (0,4,6%), sliding velocity (1, 2, 3 m/s), and sliding distance (1000, 14000, 1800 m), were utilized in this study. It was concluded that the sliding distance most significantly affected the output parameters [1]. Ponugoti et al. [10] used Fuzzy and Grey's relational analysis (FGRA) to optimize the tribological properties of hybrid reinforced Al composites. The reinforcements used were Gr and tungsten carbide (WC) in Al6061 base metal. The wear tests at 9% Gr and WC variations of 1, 2, and 3% were done using a pin-on-disk tribometer, while the wear rate and COF were estimated and optimized under varying factors of % reinforcement, load, sliding distance, and sliding velocity based on a face-centered central composite design with 30 experimental runs. The FGRA was utilized to obtain the optimal control variable values, which was to minimize both the wear rate and COF. The study further confirmed the optimal tribological conditions with experimental results validation. A monolithic reinforcement of SiC was incorporated into Al6082 for the production of MMCs using the powder metallurgy route. The tribological performance of the synthesized MMCs was optimized using Grey-Taguchi's method. An array of L27 orthogonal was used for the DOE for the wear test using a pin-on-disc tester where the volume loss and frictional force were obtained. The specific wear rate (SWR) and COF were determined, in which the GRA was used to obtain the optimum level parameters of the responses. It was deduced that out of the four parameters that had a significant influence on the friction and wear behaviour, the % volume was seen as the most influential parameter [11]. Taguchi's design was applied in the optimization of the tribological properties of Al hybrid composites using A356 alloy and 10 wt.% SiC and graphite. Compo-casting was used to produce the hybrid composites. A block-on-disc tribometer was used to perform the wear tests, where the weight percentage of graphite was 0, 3, 5 wt.%, loads (10,20, 30 N), and sliding speed (0.25, 0.5, 1 m/s) with a sliding distance of 300 m. Taguchi's method was used to analyze the SWR to obtain the optimal parameters. The study revealed that the percentage effect of load applied was the most influential on the SWR [12]. In another study by Dharmalingam et al. [13], Gray-Taguchi's method was used in the optimization of the tribological properties of Al hybrid metal composites. Alumina and molybdenum disulfide (ranging between 2 and 4 wt.%) were mixed with 5 wt.% alumina to produce MMCs using the stir casting route. A pin-on-disc tribometer was used to perform the wear experiments. The volume loss and frictional force measured were used to determine the SWR and COF. The Taguchi-GRA method was used to design the experiment and obtain the optimum level factors for SWR and COF. The interactions of the control parameters showed a meaningful influence on the tribological performance. Other studies on Taguchi-GRA include Agboola et al. [14]; Muthuramalingam et al. [15]; Unnikrishnapillai & Sanghrajka [16]; and so on.

From the reported studies, it was observed that the Taguchi-GRA method has been used to optimize the wear properties of hybrid reinforced composites. There has been no study on the optimization of the tribological properties of Al6063 with hybrid reinforcement of 2 wt.% SiC and palm kernel shell ash (PKSA). The PKSA contents varying between 0 and 6% with 2 wt.% intervals. Hence, Taguchi and GRA method at L16 orthogonal array experimental design was used in this study to optimize the responses of the dry sliding performance of the wear test done by varying the control parameters like % reinforcement, load, and sliding speed. Analysis of variance (ANOVA) was utilized to determine the contributions of each parameter and their interactions on the tribological performance of the composite of interest.

Taguchi method and grey-relational analysis

One of the most powerful and useful tools in the design of high-quality systems based on orthogonal array experiments is the Taguchi method [14,17,18]. This orthogonal array (OA) helps to reduce variance for experiments with an optimum setting of process control parameters. A simple and efficient integrated approach is introduced to determine the optimum range of designs in terms of performance, cost, and quality. The advantage of Taguchi over the traditional experimental factor is that it concentrates on the effect of variation on the process quality parameters rather than on its averages. To

Table 1
Chemical composition (%) of (a) Al6063 matrix (b) PKSA.

Constituents[a]	Si	Fe	Mn	Mg	Cu	Ti	Zn	Cr	Sn	Al
%	0.43	0.17	0.04	0.48	0.01	0.02	0.01	0.01	0.01	Bal.
Constituents[b]	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	Fe_2O_3	MnO	LOI
%	0.17	3.14	6.46	66.90	3.78	5.20	5.52	0.53	5.72	0.08	2.50

*LOI- Loss on ignition, a-Al6063 matrix, b-PKSA.

determine the parameter effects and their interactions with all the factors, the Taguchi method explores the entire design space through a small number of experiments using OA. The data obtained are then utilized in predicting the optimum combination of the design parameters, which help in the objective function minimization and constraints satisfying.

The order of sequence for Taguchi's method for the optimization process has been fully explained in Taguchi [17]. Taguchi's method employs signal-to-noise (S/N) statistical measures of performance, which are usually estimated for the target functions (responses). The S/N ratio of the response is dependent on the quality characteristics of the product or process to be optimized. The higher-the-better (HB), lower-the-better (HB), and nominal-the-best (NB) are the three different categories of S/N ratios, which are utilized in Taguchi's method. For the optimization of the tribological properties of AMCs, the lower-the-better characteristics should be used [14,17,18]. ANOVA is usually done in the determination of the experimental factors, which are statistically significant. Hence, the S/N ratio and ANOVA analyses help to predict the optimum process parameters blend. Finally, for the verification of the optimal process factors, confirmation experiments are normally performed. Taguchi's method is not appropriate for concurrent optimization of multi-objective functions [14]. Hence, the introduction of grey-relational analysis (GRA) was necessary. This study focuses on the optimization of the tribological parameters to minimize the wear rate and volume loss of the produced MMCs using Al 6063, SiC, and PKSA. This is a multi-response optimization case. For multi-response analysis, an efficient tool to be used is grey's relational analysis, where target functions are initially normalized between 0 and 1. Then, grey's relational coefficient and the overall grey relational grade (GRG) are evaluated, respectively. The GRG evaluation is used in the determination of the multiple performance characteristics, where the highest GRG value is the optimal level of the process parameters. Furthermore, to predict the ranking order as well as the percentage contribution of each factor and their interactions on the tribological properties, ANOVA is usually considered.

Materials and method

The present study utilized a palm kernel shell (PKS) obtained in Osogbo, Nigeria. The PKS was sorted, cleaned, and dried. Other procedures employed in obtaining the ash from PKS at 900 °C have been reported by Ikubanni et al. [19]. For the synthesis of the AMCs, the base alloy was Al6063 with the composition displayed in Table 1. The hybrid reinforcements used were silicon carbide (SiC) and palm kernel shell ash (PKSA) with the chemical compositions described in Table 1. The average sizes of the SiC and the PKSA particulate reinforcements are about 30 μm and 40 μm, respectively. The production technique employed was the two-stir casting method, as illustrated by several authors [20,21].

Hybrid composite synthesis

The popular liquid metallurgy method is stir casting, which was employed in the development of the composites. The composite production was by double stir casting technique in accordance with Alaneme et al. [21]. The charge calculation was performed to determine the quantities of SiC, PKSA, and Al6063 required to produce between 0 and 10 wt.% reinforcement mixes. The hybrid reinforcement particles (SiC and PKSA) were initially preheated at 250 °C to reduce moisture and improve their wettability with the base metal [22]. Using a gas-fired crucible furnace, the Al6063 alloy billets were charged into it, and the furnace was heated to a temperature of 750 °C ± 30 °C. The already melted metal was then allowed to cool to a semi-solid state in the furnace at a temperature of about 600 °C. The already preheated reinforcements of PKSA and SiC were charged into this semi-solid state Al6063 alloy melt. The slurry was manually stirred for about 10 min. The semi-solid composites were then superheated to a temperature of about 780 °C ± 30 °C and were mechanically stirred the second time for about 10 mins at an average speed of 400 rpm. The mechanical stirring was to help in improving the distribution of particulates in the molten metal matrix, thereby breaking down particle agglomerates. The molten composites were then poured into an already prepared sand mold to solidify.

Tribological characteristics

Taber Type Abrasion tester (Model No: TSE-A016) was used in determining of the wear resistance of the composites produced in accordance with ASTM D4060-16 standard. The test samples were machined to dimensions of diameter (100 mm) and thickness (5 mm). The sample's surface was placed on the turntable platform of the Taber abrasion machine. It was then gripped at constant pressure by two abrasive wheels lowered onto the surface of the sample. Each sample was subjected to four different masses (loads) of 250, 500, 750 and 1000 g, and four different rotating speeds of 250, 500, 750, and 1000 rpm. Due to the rubbing action between the sample and the abrasive wheels during the machine rotation, loose composite debris from the sample was generated. Therefore, the weights before (initial weight) and after (final weight) of the test were obtained after 15 mins duration of the abrasion testing.

The wear properties of the composites were then determined as follow in Eqs. 2–(3). The mass loss (g) and volume loss (mm^3) were determined using Eqs. (2a) and (2b), respectively:

$$Mass\ loss = Initial\ mass\ (m_i) - Final\ mass\ \left(m_f\right) \tag{2a}$$

$$Volume\ loss = \frac{mass\ loss}{\rho} \tag{2b}$$

The Taber wear rate index was obtained using the relation as shown in Eq. (3):

$$Taber\ Wear\ Index,\ I = \frac{m_i - m_f}{T} \times\ 1000 \tag{3}$$

Where ρ is the density of each composite composition, T is the time of test cycles (minutes), and I is the Taber wear index.

Experimental design and optimization

Design of experiment and Taguchi method

The factors of consideration in this study are three (3); namely: reinforcement, load, and speed, while for each factor, four levels were selected. Reinforcement has levels 2, 4, 6, and 8 wt.%; load has levels 250, 500, 750, and 1000 g; while speed has levels 250, 500, 750, and 1000 rpm.

Taguchi's technique was utilized in this study for the optimization of the wear index and the volume loss of the synthesized AMCs. Based on three process parameters with four different levels considered in this study, an L_{16} orthogonal array was selected. In Taguchi's method, the target function values are usually converted to signal-to-noise (S/N) ratios. Since the two (2) target functions (wear index and volume loss) were required for minimization, the performance characteristics chosen for determining the S/N ratio is the smaller-the-better using Eq. (4).

$$S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{4}$$

where n and y_i are replication number for each test and the i_{th} value of the performance characteristics.

Analysis of variance (ANOVA)

ANOVA was employed to analyze the influence of % reinforcement, load, and sliding speed on the wear rate index and volume loss of the AMCs. The ranking importance of the process parameters on the target function was obtained through ANOVA, hence confirming the Taguchi's method results. The Taguchi and ANOVA analyses were performed using Minitab 14 (Statistical software) in this study.

Confirmation Test

To validate optimum conditions after wear rate (WR_{opt}) and volume loss (VL_{opt}) have been established based on the Taguchi's method, a confirmation test was conducted as suggested by [14,23]. The Equations (5–6) were utilized to estimate the optimum values of the responses.

$$WR_{opt} = m_W + (A_3 - m_W) + (B_1 - m_W) + (C_1 - m_W) \tag{5}$$

$$VL_{opt} = m_V + (A_1 - m_V) + (B_1 - m_V) + (C_1 - m_V) \tag{6}$$

where ($A_3B_1C_1$) and ($A_1B_1C_1$) denote the optimum level figures of wear rate and volume loss, respectively. m_W and m_V are the average of all the WR_{opt} and VL_{opt}, respectively, derived in the study. Eqs. (7) and (8) were utilized to estimate the confidence intervals (CI) for each response to ascertain if the predicted optimal figures of the responses are in concordance with the experimental figures [18].

$$CI = \sqrt{F_{\alpha,\ 1, fe} V_e \left[\frac{1}{n_{eff}} + \frac{1}{R}\right]} \tag{7}$$

$$n_{eff} = \frac{N}{1\ + T_{dof}} \tag{8}$$

Table 2
Process parameters, responses and their S/N ratios.

Exp No.	Process parameters			Responses (Target functions)		S/N ratio for various responses	
	Reinforcement (wt.%)	Load (g)	Speed (rpm)	Wear index (g/min)	Volume loss (mm^3)	Wear index	Volume loss
1	2	250	250	0.00297	14.973	50.5449	-23.5062
2	2	500	500	0.00355	19.902	48.9881	-25.9779
3	2	750	750	0.01713	95.928	35.3264	-39.6389
4	2	1000	1000	0.07449	417.236	22.5577	-52.4076
5	4	250	500	0.00499	28.448	46.0328	-29.0810
6	4	500	250	0.00473	26.928	46.5083	-28.6041
7	4	750	1000	0.06515	378.784	23.7213	-51.5678
8	4	1000	750	0.02863	163.090	30.8645	-44.2485
9	6	250	750	0.00101	57.967	59.9541	-35.2636
10	6	500	1000	0.01672	96.406	35.5353	-39.6821
11	6	750	250	0.00639	36.863	43.8859	-31.3318
12	6	1000	500	0.01791	103.248	34.9395	-40.2776
13	8	250	1000	0.01499	87.471	36.4857	-38.8373
14	8	500	750	0.01199	70.000	38.4214	-36.9020
15	8	750	500	0.01247	72.763	38.0848	-37.2382
16	8	1000	250	0.00840	49.027	41.5144	-33.8087

Grey relational analysis (GRA)

GRA entails to initially normalize the experimental results usually between 0 and 1. The criteria chosen for all the responses is the smaller-the-better performance which can be evaluated using Eq. (9).

$$\text{The smaller} - \text{the} - \text{better}, y_i(s) = \frac{maxx_i(s) - x_i(s)}{maxx_i(s) \; - \min x_i(s)} \tag{9}$$

Determination of the grey relational coefficient (GRC) is usually conducted after the experimental results have been normalized, which is usually performed by utilizing Eqs. (10) and (11).

$$\varepsilon_i(s) \; = \; \frac{\Delta_{min} \; + \varphi \Delta_{max}}{\Delta_{oi}(s) + \varphi \Delta_{max}} \tag{10}$$

where $\Delta_{oi}(s)$ is the deviation sequence evaluated by utilizing Eq. (11)

$$\Delta_{oi}(s) = \; |x_o(s) - x_i(s)| \tag{11}$$

$x_i(s)$, min $x_i(s)$, and max $x_i(s)$ are the comparability sequence, minimum comparability sequence, and maximum comparability sequence, respectively while, $x_o(s)$ is the referential sequence, φ is the coefficient of identification, ranging between 0 and 1. According to Naqiuddin et al. [24]; Acir et al. [25], and Chamoli et al. [26], 0.5 is normally selected for φ because the utilization of 0 or 1 has no influence on ranking order of the parameters.

Results and discussion

Signal-to-noise ratio (S/N) analysis of the responses

The response characteristics of the process parameters, as well as the signal-to-noise ratio (S/N ratios), are displayed in Table 2. The experimental runs gave different responses per run. Further analyses of the results are explained in details in subsequent sub-sections.

Analysis of a response (Wear index)

The mean S/N ratios and the process parameters ranking order on the wear index value were obtained. The major influence of each parameter on the wear index of the synthesized AMCs is displayed in Fig. 1a. The process parameters having the highest S/N ratio will contribute to the optimal process parameter variants [12,27]. The process parameters required for the optimal condition for the wear index were obtained. This was when the reinforcement percentage was 6 wt.%, at an applied load of 250 g and a sliding speed of 250 rpm. By implication, when 2 wt.% of SiC and 4 wt.% of PKSA were incorporated into Al6063 as hybrid reinforcements at an applied load of 250 g with a sliding speed of 250 rpm ($A_3B_1C_1$), the optimum wear index can be attained. Hence, indicative of the optimum condition for the wear index. Based on the ranking, the sliding speed influenced the optimum value the most followed by the load, while reinforcement percentage weight had the lowest effect on the wear index.

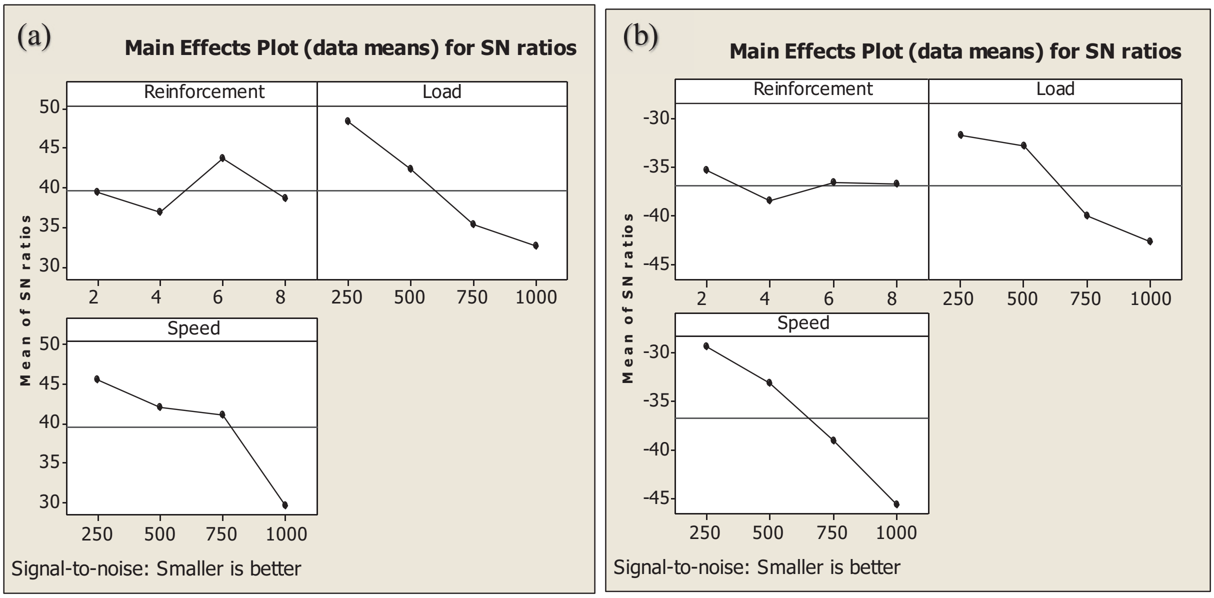

Fig. 1. S/N ratio main effect plot of each parameter on (a) Wear index (b)Volume loss (Taguchi).

Table 3a
ANOVA results on the wear index.

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value	Contribution (%)	R-sq
Reinforcement	3	99.12	99.12	33.04	1.47	0.313	6.97	0.905
Load	3	609.06	609.06	203.02	9.05	0.012	42.83	
Speed	3	579.41	579.41	193.14	8.61	0.014	40.74	
Error	6	134.53	134.53	22.42			9.46	
Total	15	1422.12					100%	

Analysis of volume loss target functions

The average signal-to-noise ratios, as well as the ranking order of the process parameters of reinforcement, load, and speed on the volume loss value were obtained. The effect of each process parameter on the volume loss is shown in Fig. 1b. It was shown that the sliding speed has a higher influence on the volume loss among the considered process parameters. The influence of applied load was also ranked second, while the reinforcement effect was ranked least. For the optimum value for the volume loss, 2 wt.% reinforcement inclusion in the AMCs is required, with 250 g applied load, and 250 rpm sliding speed. These are obtained from Fig. 1b, where the optimum value is $A_1B_1C_1$ ($A_1 = 2$ wt.% reinforcement, $B_1 = 250$ g load, $C_1 = 250$ rpm sliding speed).

Analysis of variance of the responses

Wear index

According to Agboola et al. [14] and Sarıkaya & Güllü [28], Taguchi analysis results should be validated using analysis of variance (ANOVA) for the statistical reliability of the results. Hence, the percentage contribution of each parameter of the AMC samples on the wear index was determined. The ANOVA results on the wear index of the AMC samples, in Table 3a, display the amount of influence of each process parameter on the response in terms of percentage contributions. Based on the ANOVA analysis carried out, the higher percentage contribution was derived to be 42.83%, which was attributed to the load applied. The percentage contribution of speed was 40.74%, while the least percentage contribution of 6.97% was observed for the percentage reinforcement weight. However, different ranking results were obtained between the Taguchi's method main effect plots and the ANOVA outcomes. The Taguchi method showed the ranking order as speed, load, and reinforcement, while the ANOVA results showed the ranking order as load, speed, and reinforcement. This implies that both the load and speed have the greatest impact on the wear index, while reinforcement has the least influence. This study is in agreement with the work of Veličković et al. [12]. In the study, the reinforcement addition of graphite was observed to have less significance compared to the load applied and sliding speed of the composites considered. Therefore, increasing applied load and speed have high effects on the wear index of the AMCs. As reported by Kumar & Birru [29], the increase

Table 3b
Process parameter effects on volume loss (ANOVA results).

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value	Contribution (%)	R-sq
Reinforcement	3	18.1	18.1	6.033	0.97	0.467	1.79	0.963
Load	3	347.55	347.55	115.85	18.59	0.002	34.35	
Speed	3	608.73	608.73	202.909	32.55	0.000	60.16	
Error	6	37.4	37.4	6.233			3.70	
Total	15	1011.78					100%	

Table 4
Predicted and Experimental results at optimum conditions for each response.

Response	Optimum condition	Predicted optimum value	Optimum value by Experiment
Wear index (g/min)	$A_3B_1C_1$ (Reinforcement = 6 wt.%; Load = 250 g; Speed = 250 rpm)	0.00122	0.00270
Volume loss (mm^3)	$A_1B_1C_1$ (Reinforcement = 2 wt.%; Load = 250 g; Speed = 250 rpm)	13.825	14.973

in applied load could lead to an increase in the tribological properties such as wear rate, coefficient of friction, and so on. This is as a result of a higher level of plastic deformation caused by the increased load.

In addition, the p-value of each of the process parameters revealed those that have significant influences on the wear index. The p-value of reinforcement, load, and speed is 0.313, 0.012, and 0.014, respectively. The p-value of the reinforcement process parameter is far above 0.05 confidence level; hence, making reinforcement of no significance on the wear index value. The load and speed have a great influence on the wear index values of the composites considered.

Volume loss

Table 3b shows the ANOVA results and the contribution ratios of the effects of the three parameters on the volume loss. The contribution ratios of the process parameters based on the ANOVA analysis showed that the speed has the highest influence with a percentage value of 60.16%, followed by the applied load with a percentage contribution of 34.35%, while that of reinforcement is 1.79%. The percentage contribution ratio of reinforcement is very low; hence, its influence on the volume loss might be considered to be insignificant compared to both the speed and load. Similarly, the ANOVA results showed the level of significance of the process parameters on the volume loss. The *p*-value of the reinforcement (0.467) showed no level of significance, while the p-values of speed (0.000) and load (0.002) showed high levels of significance of these parameters on the volume loss. The p-values for both the load and speed are less than 0.05, which implies that the two parameters are statistically significant and have an influence on the response. The experimental values showed that as the load and speed increase, the volume loss of the composites increased without recourse to the reinforcement weight percentage. The volume loss was directly proportional to speed and load, as reported in the study of Halil et al. [6], where the higher the speed and load, the more the volume loss of the material from the samples. This study showed that both the Taguchi analysis and ANOVA method utilized ranked the speed as the most influencing factor, followed by applied load, while percentage reinforcement weight is ranked the least influencing factor. Since the order of ranking for both analyses gave the same result, the utilization of these optimization tools is confirmed to be reliable as stated by Agboola et al. [14]; and Chamoli et al. [26].

Confirmation test

A confirmation test was carried out in this study to determine the accurate optimization values of the tribological properties evaluated. The predicted and experimental results at optimum were confirmed to be within the confidence interval (CI) calculated based on Eqs. (7) and (8), where the following values $F_{0.05,1,3} = 10.128$, $V_{eWI} = 22.42$, $V_{eVL} = 6.233$ Table 2b), $R = 2$, $N = 16$, $T_{dof} = 9$ and $n_{eff} = 1.6$ were substituted into Eqs. (7) and ((8) to obtain the CI. From Table 4, the CI computed values for the experimental optimum and predicted values are within the acceptable limits for each of the target functions.

Grey relational analysis (GRA)

In GRA, the two target functions were reduced to a single objective function termed multiple performance characteristics (MPC). The main objective is to optimize the wear index and volume loss target functions. Table 5 displays the results of the normalized response, grey's relational coefficient (GRC), grey's relational grade (GRG), and ranks, which were obtained by the application of Eqs. (9–11). Experiment 1 gave the maximum MPC (Table 5). It has been established that an experiment with the highest GRG in all the experimental runs gives the optimum MPC [14]. GRG was used to estimate the order of ranking for each process parameter through the response generated. The ranking order shows speed > load > reinforcement. The speed of rotation is considered as the most influential, followed by the applied load, and finally by reinforcement. Experiment 1 was found to be the highest.

Table 5
GRA optimized results.

Exp. No.	Normalized Results		Grey Relational Coefficients		GRG	Rank
	Wear Index	Volume loss	Wear Index	Volume loss		
1	0.9733	1.0000	0.9492	1.0000	0.9746	1
2	0.9653	0.9877	0.9352	0.9761	0.9556	2
3	0.7806	0.7988	0.6950	0.7130	0.7040	12
4	0.0000	0.0000	0.3333	0.3333	0.3333	16
5	0.9457	0.9665	0.9021	0.9372	0.9197	4
6	0.9494	0.9703	0.9080	0.9439	0.9260	3
7	0.1271	0.0956	0.3642	0.3560	0.3601	15
8	0.6241	0.6318	0.5709	0.5759	0.5734	14
9	1.0000	0.8931	1.0000	0.8239	0.9119	5
10	0.7862	0.7976	0.7004	0.7118	0.7061	11
11	0.9267	0.9456	0.8721	0.9018	0.8870	6
12	0.7700	0.7806	0.6849	0.6950	0.6900	13
13	0.8097	0.8198	0.7244	0.7351	0.7297	10
14	0.8505	0.8632	0.7698	0.7852	0.7775	8
15	0.8440	0.8563	0.7622	0.7768	0.7695	9
16	0.8994	0.9153	0.8325	0.8552	0.8438	7

The main effect of each process parameter of the typical wear sample (Figure SM1) is shown in Figure SM2. The optimum condition for the multiple characteristics of the responses is $A_3B_1C_1$. $A_3B_1C_1$ means that when the reinforcement weight percentage is 6 wt.%, loads applied is 250 g, and speed is 250 rpm, then the optimum value can be obtained. As shown in Table SM1, the results of the GRG and the percentage contribution of the parameters were evaluated using ANOVA. The two main processing factors with the maximum influence on the MPC having a percentage contribution of 47.38% and 23.9% are speed and loads, respectively. This is also confirmed from the ranking order from the GRG response (Table SM2). The p-value of speed is below 0.05 (Table SM1); hence, the influence of speed is statistically significant, while the ranking order of the parameters is speed > loads > reinforcement.

The three process factors and four levels used in this study are presented in Table SM3. The S/N ratios responses and ranking order of the wear index and volume loss vs. reinforcement, load, and speed, are respectively shown in Table SM4 and Table SM5. These are important to further ascertain the most influential factor on the response considered.

Conclusion

The tribological properties of aluminium metal composites produced using hybrid reinforcements through double stir casting route have been optimized with the utilization of the combined Taguchi and Grey's relational analysis methods. Parameters such as reinforcement percentage weight, load, and speed were used as the processing parameters, for which their effects were analyzed on the wear index and volume loss. ANOVA was utilized to evaluate and validate the experimental results. It can be concluded that:

i At $A_3B_1C_1$ (Reinforcement (6 wt.%), Load (250 g), speed (250 rpm)), the optimal conditions for the wear index were obtained, while at $A_1B_1C_1$ (Reinforcement (2 wt.%), Load (250 g), speed (250 rpm)), the optimal conditions for the volume loss were obtained.
ii Based on the analysis performed using Taguchi's method and GRA, the most significant parameter that influences the wear index and volume loss is the speed.
iii The confirmatory test performed at a 95% confidence interval showed that the predicted and experimental results are within the acceptable range.
iv The two methods used in this study showed that they are reliable methods for the optimization of tribological properties.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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