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Rohinikumar Chebolu*, Ramanaiah Nallu, Ratnam Chanamala

Andhra University, A.U. College of Engineering(A), Department of Mechanical Engineering, Visakhapatnam, Andhra Pradesh-530003, India
**Corresponding author. E-mail: rohinikumar.rs@andhrauniversity.edu.in*

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EFFECT OF TiB_2 ON TRIBOLOGICAL PROPERTIES OF AS-CAST Zn-Al-Cu/SiC COMPOSITES USING TAGUCHI AND ANOVA TECHNIQUES

The present study presents an evaluation of the tribological properties of the as-cast Zn-Al-Cu alloy-based hybrid metal matrix composite and also the effect of the weight percent of TiB_2. The hybrid composites were fabricated using ultrasonic assisted stir casting with 5 wt.% silicon carbide (SiC) and varying X wt.% (0, 5, 10) of titanium diboride (TiB_2). A pin-on-disc type tribometer was used to ascertain the tribological properties like the wear rate and coefficient of friction (COF). The influence of various parameters like the weight percentage of TiB_2 particles (0, 5 and 10 %), loads (10, 20 and 30 N) and sliding speeds (0.25, 0.5 and 1 m/s) on the tribological behaviour was determined using the L9 orthogonal array for Taguchi and ANOVA.

Keywords: Zn-Al-Cu alloy, HMMC, tribological properties, Taguchi and ANOVA

INTRODUCTION

Among the Zamak alloys, ZA27 is generally known for its industrial bearing applications because of their excellent tribological and mechanical properties. Several researchers have reported on Zn-Al-Cu alloy-based metal matrix composites and the improvement in their properties with the addition of ceramic reinforcement particles such as SiC, TiB_2, alumina, graphite, zirconia and titania etc. [1]. The effect of hybridization in composites plays a major role in the improvement of the tribological properties.

Wear is a common service occurrence that results in the gradual deterioration of materials over time, eventually leading to premature failure. Wear is an issue in many engineering applications, and it costs industry large sums of money to replace or repair equipment that has worn out and no longer serves a useful purpose. When compared to unreinforced aluminium alloys, the wear performance of particle reinforced aluminium MMCs has been observed to be better.

For various weights and sliding distances, the promising effects of silicon carbide reinforcement were investigated [2-6]. It was observed that in some of the studies, the composites exhibit a lower wear rate without the reinforcements. The dimensional stability and wear resistance of zinc-aluminium based alloys enhanced with an addition of the ceramic particles were improved in dry and lubricated environments [4, 7-9].

Many researchers have studied the tribological performance of hybrid composites with an zinc alloy matrix. Certain parameters like, the reinforcement particle's size, type and its quantity to be added in the matrix are were optimised in order to produce a composite material with improved qualities that would meet the desired criteria. Some parameters influence the properties of the composite materials and these parameters were optimized to obtain the maximum values of the composite properties. The properties of the composites were observed and increased in order [10, 11]. Due to the increase in demand for hybrid composites, this study aims to improve the primary tribological properties and development of hybrid metal matrix composites by adding various weight percentages of reinforcements and thereby optimize the tribological parameters of zinc-aluminium hybrid metal matrix composites. The wear resistance of hybrid Zn-Al matrix composites supplemented with SiC and TiB_2 particles has been studied [8, 12, 13].

According to a review of the available scientific literature, there are not many articles or studies on the hybridization effect of composite materials based on zinc-aluminium alloys. The ultrasonic assisted stir casting technique was used to produce the hybrid composites that were and experimentally investigated throughout this study. The goal was to study the tribological properties of these hybrid metal matrix composite materials and optimize the wear testing parameters of the zinc-aluminium alloy reinforced with SiC and TiB_2 particles.

The Taguchi technique was employed to investigate the effects of the weight percentage of titanium diboride reinforcement, normal load, and sliding speed on the tribological behaviour of the hybrid metal matrix composites. The optimal values of the investigated factors that impact the particular wear rate and coefficient of friction were reported in this article [12, 14].

MATERIALS AND METHODS

Matrix

The as-cast Zn-Al-Cu alloy was considered as the base alloy material for this research. The as-cast Zn-Al-Cu alloy ingots of a rectangular shape with the dimensions 150 x 150 x 25 mm were prepared by the liquid metallurgy route as per the ASTM B669-82 standard and the chemical composition of this alloy is given in Table 1 [15]. The purity of zinc is 99.90%, aluminium as 99.98% and copper 99.00%. The aluminium and copper were put in a crucible and heated upto 650°C and then the zinc was added. The stirring process was taken place for a period of 5 min and the degassing agent C_2Cl_6 was also added [16]. No grain refinement treatment was performed during this process.

TABLE 1. **Chemical composition of as-cast Zn-Al-Cu alloy according to ASTM B669-82**

Material	Zinc	Aluminium	Copper	Magnesium
Percentage composition [wt.%]	Balance	25-28	2.0-2.5	0.01-0.02

Reinforcement

Commercially available ceramic particles, i.e. silicon carbide and titanium diboride of average particle sizes 20 microns and 30 microns with 99.00% purity were procured from Nano shell, India. The details of the ceramic particles are presented in Table 2.

TABLE 2. **Properties of reinforcement materials**

Reinforcement	Density [g/cc]	Melting point [°C]	Young's Modulus [GPa]	Tensile strength [MPa]
SiC	3.21	2730	137	625
TiB_2	4.52	2970	575	754

Preparation of composites

The as-cast Zn-Al-Cu alloy was put into a graphite crucible and heated up to 680°C for 15 min. To improve the wettability, 2.7 wt.% of hexafluoro titanate salt (K_2TiF_6) was added to the molten alloy [16]. The 5 wt.% of SiC and X wt.% TiB_2 (X = 0, 5, 10) particles were added to the molten alloy. Before adding these ceramic particles to the molten alloy, they were preheated up to 800°C, and then maintained at this temperature for a period of one hour. The molten alloy was then conventionally mixed with a mechanical stirrer at 85 rpm and also the rotating speed was maintained constant for 15 minutes to ensure appropriate distribution of the reinforcement. An ultrasonic probe, manufactured of titanium alloy, was then submerged to 3/4 – of its height into the molten slurry in the crucible.

A 20 kHz ultrasonic processing frequency was employed for sonication.Tthe ultrasonic energy pulses were used for 22 min to disperse the agglomerations of the reinforcements in the molten mixture [17]. After the sonication process, the graphite crucible taken out of the furnace and the hybrid metal matrix composite in molten form was poured into a mould of mild steel material.

The casting mould was preheated to 560°C and then filled with the molten zinc-aluminium-copper alloy. A wire electric discharge machining (WEDM) machine was utilised to produce composite specimens for testing in accordance with ASTM standards. Table 3 shows the composition of the as-cast samples and their designation used further in this paper.

TABLE 3. **Wt.% of composite samples**

S. No.	As-cast Zn-Al-Cu-Alloy [wt.%]	SiC [wt.%]	TiB_2 [wt.%]
1	95	5	0
2	90	5	5
3	85	5	10

A pin-on-disc tribometer was used to assess the tribological characteristics of the produced hybrid composites according to ASTM G99 [18]. Figure 1 depicts the tribometer configuration used to conduct the tests. Table 2 shows the actual process parameters used to conduct the wear test, as well as the values assigned to them. The test specimens were 10 mm x 10 mm x 15 mm in length, breadth, and height. For a track diameter of 50 mm, the wear performance was determined under varied loads and sliding speeds, while the coefficient of friction was recorded using tribometer software to obtain a mean value for each test condition and composite.

Fig. 1. Pin-on-disc tribometer

EXPERIMENTAL DESIGN

The experiments were conducted on composites to investigate the wear rate and COF by considering the following wear test parameters at different levels i.e. loads of 10, 20 and 30 N, sliding speeds of 0.25, 0.50 and 1.0 m/s) and the remaining parameters were constant with a sliding distance of 300 m. Table 4 lists all of the factors and respective levels that influence the wear rate and COF.

By using design of experiments, a total of nine experiments were conducted. Table 5 shows the experimental design of the orthogonal array L9 for the three factors and three levels by using the Taguchi three level mixed design from Minitab18 statistical software.

The S/N ratio "the lower the better" feature as utilized to analyse the wear rate and COF. The equation to calculate the *S*/*N* ratio is presented below

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

where y_i is the outcome of the i^{th} experiment for each trial, *S*/*N* is the signal-to-noise ratio, n is the number of repeated trials, and *S*/*N* is the signal-to-noise ratio. On the basis of *S*/*N* analysis, the *S*/*N* ratio for each level of influencing factors is derived. To assess statistically significant factors, statistical analysis of the variables was conducted. It is possible to predict the best combination of parameters. Table 5 shows the *S*/*N* ratio for the wear rate and COF estimated using an orthogonal array for various combinations of affecting elements.

TABLE 4. **Wear test factors and levels**

Factor/Level	I	II	III
A – wt.% TiB_2	0	5	10
B – Load [N]	10	20	30
C – Sliding speed [m/s]	0.25	0.5	1

TABLE 5. **Experimental matrix L9 orthogonal array**

S. No.	Wt.% TiB_2 [%]	Load [N]	Sliding speed [m/s]	Wear rate [mm^3/km]	Coefficient of friction [COF]	SNRA-Wear rate	SNRA-COF
1	0	10	0.25	5.962	0.384	–15.5078	8.313376
2	0	20	0.5	4.521	0.483	–16.2863	6.321057
3	0	30	1.0	4.032	0.555	–16.9416	5.11414
4	5	10	0.5	4.103	0.324	–12.262	9.7891
5	5	20	1	3.976	0.493	–13.9376	6.143062
6	5	30	0.25	3.163	0.504	–11.7385	5.951389
7	10	10	1.0	3.502	0.357	–10.8863	8.946636
8	10	20	0.25	2.983	0.399	–12.0042	7.980542
9	10	30	0.5	2.13	0.423	–12.319	7.473193

RESULTS AND DISCUSSION

Signal-to-noise ratio results

The impact of the observed control factors, TiB_2 content in the hybrid composite, load, and sliding speed, was validated by S/N ratio analysis. The performance with the lowest variance was obtained by combining the influencing parameters with the highest S/N ratio. The control parameter with the greatest effect is defined by the difference between the highest and minimum value of the mean of S/N ratios.

If the difference between the mean S/N ratios is higher, the control parameter will have a larger effect. Tables 6 and 7 demonstrate how the control factors affect the wear rate and COF, respectively. The value of the TiB_2 weight percentage is the most prominent characteristic impacting the wear rate and then load for COF, according to the ranking of parameters. For both the wear rate and COF, the sliding speed has the least impact. The major impact charts for the observed testing parameters on the wear rate and COF are shown in Figures 2 and 3. Figure 2 depicts the effect of the investigated factors such as the TiB_2 weight percentage, load, and sliding speed, on the wear rate.

TABLE 6. **Response table for signal-to-noise ratios for wear rate**

Smaller is better

Level	A	B	C
1	–16.25	–12.89	–13.08
2	–12.65	–14.08	–13.62
3	–11.74	–13.67	–13.92
Delta	4.51	1.19	0.84
Rank	1	2	3

TABLE 7. **Response table for signal-to-noise ratios for COF**

Smaller is better

Level	A	B	C
1	6.583	9.016	7.415
2	7.295	6.815	7.861
3	8.133	6.180	6.735
Delta	1.551	2.837	1.127
Rank	2	1	3

The measured parameter has no substantial impact on the wear rate if it is nearly horizontal line. A steep vertical line, on the other hand, suggests that the measured parameter has the greatest impact. The TiB_2 content, followed by the load, has the largest impact on the wear rate. The residual plots of the wear rate and COF to fit into the residuals are shown in Figures 4 and 5. The interactions between the parameters and their mutual impact on the wear rate and COF for the studied composite materials are shown in Figures 6 and 7.

Fig. 2. Main effect plots for S/N Ratios for wear rate

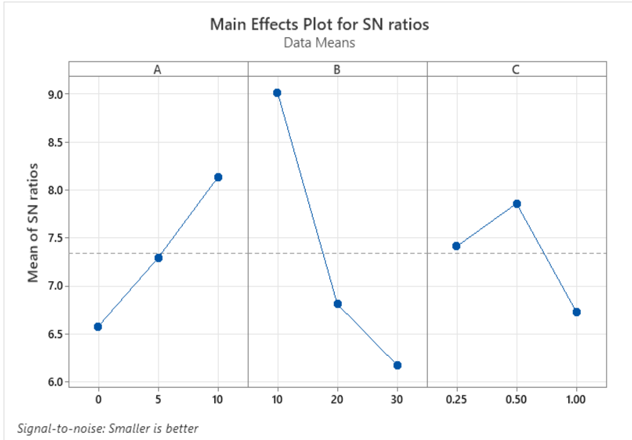

Fig. 3. Main effect plots for S/N Ratios for COF

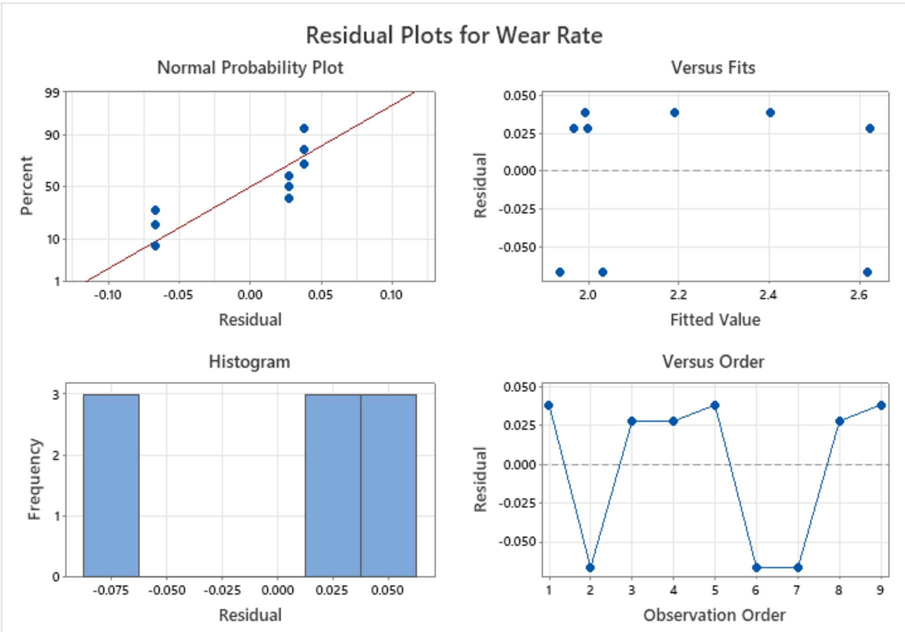

Fig. 4. Residual plots for wear rate

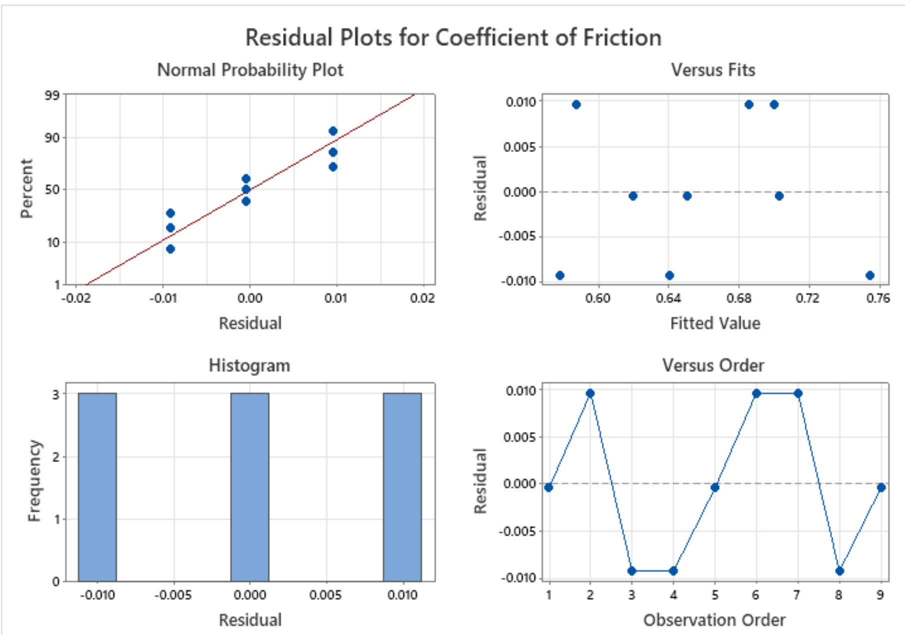

Fig. 5. Residual plots for COF

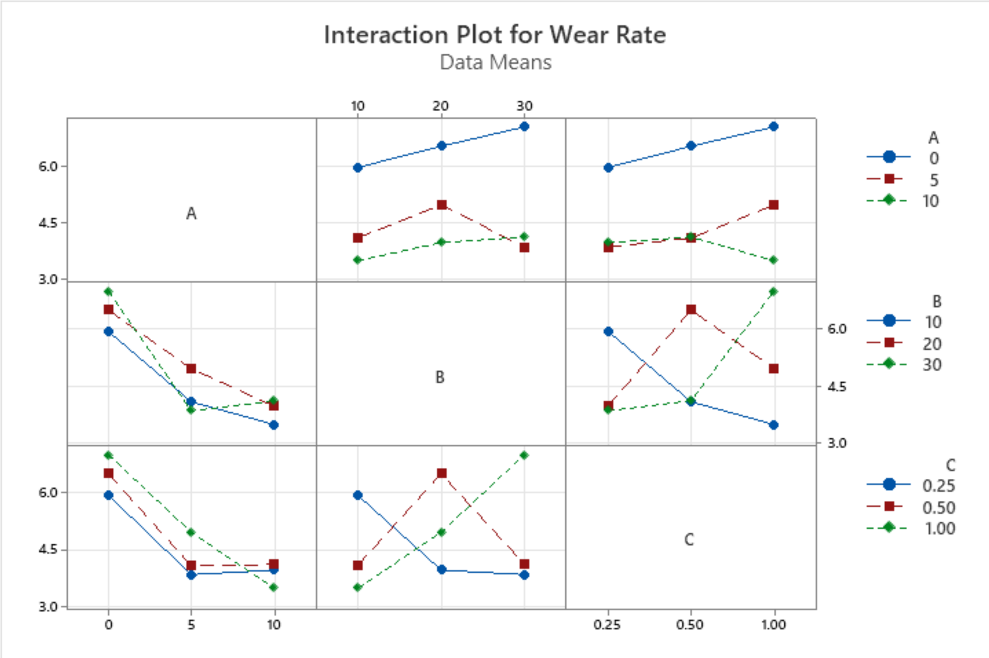

Fig. 6. Interaction plots for wear rate

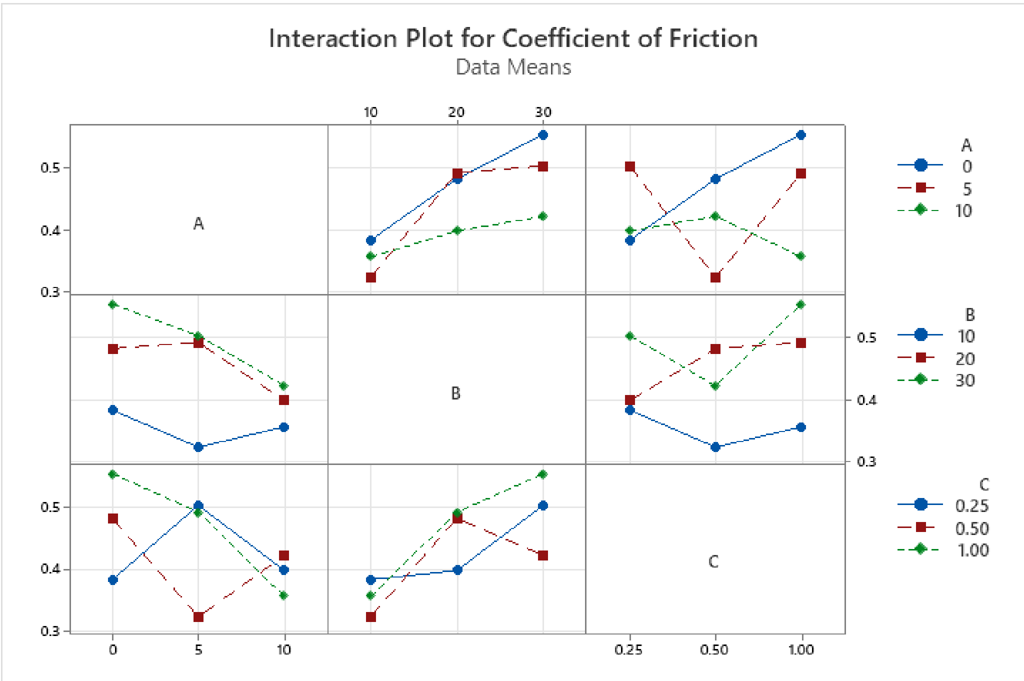

Fig. 7. Interaction plots for COF

The wear rate and COF both decrease as the TiB_2 content in the hybrid composite is raised. Increases in sliding speed and load, results in a rise in the wear rate and COF. When the TiB_2 content is increased from 0 to 5%, the wear rate grows rapidly. An increment in the TiB_2 content results in a considerably lower increase in the wear rate. The load obviously has the second highest impact on the wear rate, whereas the sliding speed has the least. When the load is increased from 10 to 20 N, the COF rises quickly, but it grows somewhat more gradually at 30 N.

Analysis of variance results

The outcomes of the experiments were analysed using analysis of variance (ANOVA). This approach may be employed to see how the examined parameters affect the wear rate and COF. The dominating factor and its percentage contribution are shown in the analysis of variance.

Table 8 presents the analysis of variance for S/N ratios for the wear rate and COF. Three variables were considered, as well as their interactions. The analysis was carried out using a significance level of 0.05, i.e.

a confidence level of 95%. Sources having a p-value of 0.05 were considered statistically significant contributors to the performance metrics.

TABLE 8. **Analysis of variance for transformed response**

Source	DF	Adj SS	Adj MS	F-Value	p-Value	Percentage of contribution
A	2	0.005436	0.002718	10.18	0.089	65.06
B	2	0.018480	0.009240	34.62	0.028	21.51
C	2	0.002893	0.001447	5.42	0.156	13.28
Error	2	0.000534	0.000267			0.15
Total	8	0.027343				

Analysis of variance results

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Table 8 reveals that the TiB_2 content has the greatest impact on the wear rate (65.06%). Other variables, such as sliding speed (13.28%) and load, have a lower impact. Figure 8 presents a contour plot and a surface plot, respectively, showing the relationship between the wear rate and TiB_2 content and load. Figure 9 illustrates a contour plot and a surface plot showing the relationship between COF and load and sliding speed. The wear rate and COF regression equations were generated from ANOVA and are indicated in Equations (2) and (3):

$$\text{COF}^{0.5} = 0.658 + 0.029A_1 + 0.003A_2 - 0.031A_3 + - 0.062B_1 + 0.018B_2 + 0.044B_3 - 0.004C_1 - 0.019C_2 + 0.023C_3 \tag{2}$$

$$\text{Wear rate}^{0.5} = 2.197 + 0.353A_1 - 0.123A_2 - 0.230A_3 + - 0.084B_1 + 0.064B_2 + 0.020B_3 - 0.062C_1 + 0.007C_2 + 0.0558C_3 \tag{3}$$

a) b)

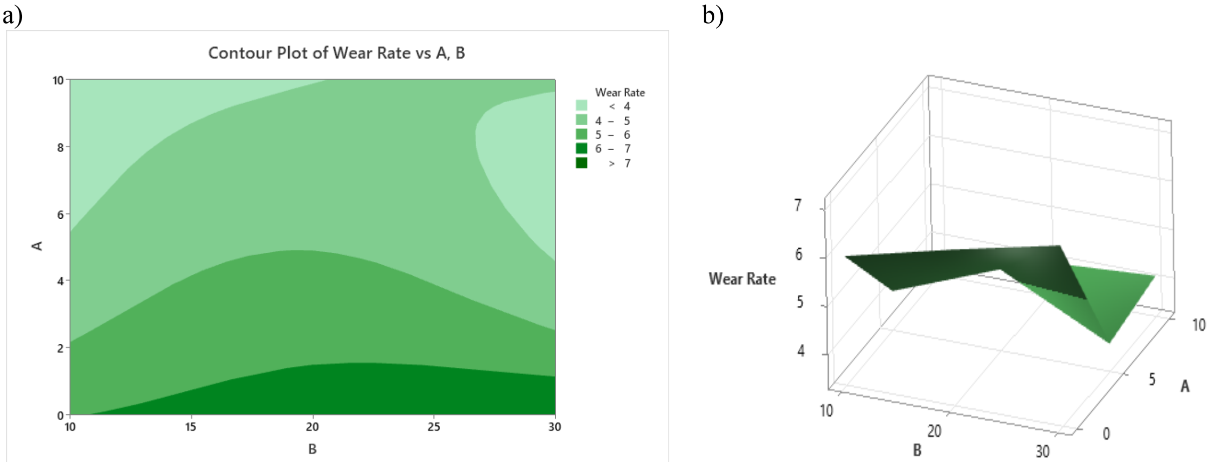

Fig. 8. a) Contour plots of wear rate vs A, B, b) surface plots of wear rate vs A, B

a) b)

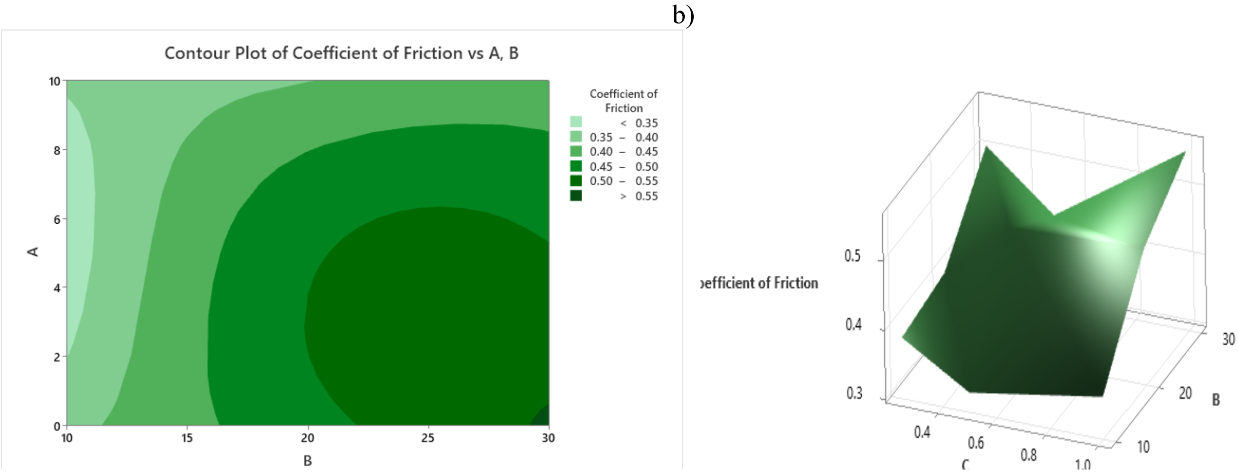

Fig. 9. a) Contour plots of COF vs A, B, b) surface plots of COF vs B, C

Scanning electron microscope analysis

Figure 10 shows a micrograph of the composite taken by means of a scanning electron microscope. The reinforcement particles are dispersed equally across the matrix material, and the presence of silicon carbide, as well as the lack of inclusions and segregations, were confirmed by microscopic analysis. In the zoomed micrograph, the hexagonal form clearly reveals the presence of titanium diboride particles.

Figure 11 depicts the worn surface for the situations of maximum and minimum wear rates. The lowest wear rate was achieved with a higher reinforcement weight percentage, a medium load, and a moderate sliding velocity.

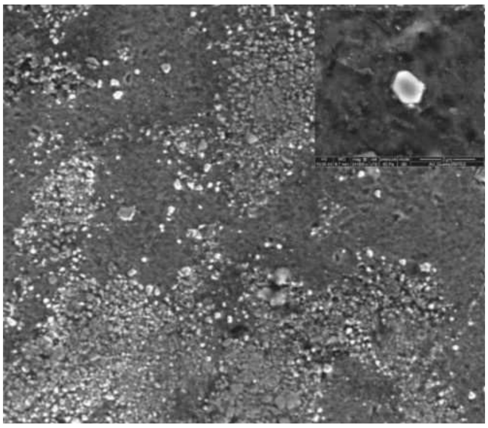

Fig. 10. SEM micrograph of Zn-Al-Cu/5%SiC/10%TiB_2 hybrid composite

a)

b)

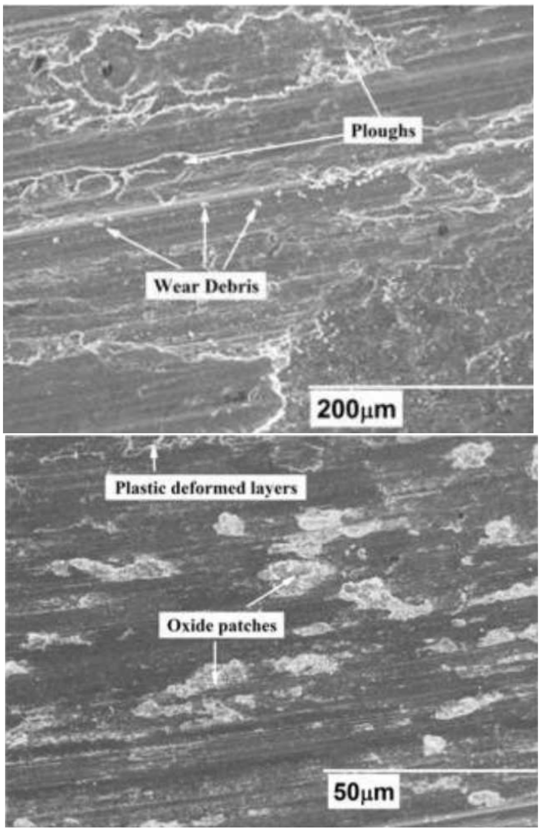

Fig. 11. SEM micrographs for worn surfaces: a) at maximum wear rate, b) at minimum wear rate of Zn-Al-Cu hybrid composite

Figure 11a depicts the worn surface of the composites as a function of the maximum wear rate, including plough marks and shallow grooves, as well as wear debris. At a lower weight % of reinforcement, a lower load, and a medium sliding velocity, the minimal wear rate was achieved. Figure 11b illustrates the worn surface of the composites in relation to the lowest wear rate due to the lower load and medium sliding velocity with evidence of certain plastic deformed layers and distributed oxide patches over the region. The temperature at the contact surface rose as the sliding velocity increased, resulting in the production of oxide layers.

Conformation test

An appropriate confirmation test was utilised to validate the advancement of the performance of the characteristics based on the discovered optimal settings. Equation (4) is used in the confirmation test.

$$Wr = Wr_m + (A_3 - Wr_m) + (B_1 - Wr_m) + (C_3 - Wr_m) \quad (4)$$

where Wr_m is the overall mean value of the wear rate, *A3, B1*, and *C3* are the S/N responses for primary variables at different levels, and Wr_m is the overall mean value of the wear rate. Based on these figures, the optimal wear rate (*Wr*) was established and confirmed to be 2.042 dB. The following confidence interval (*CI*) was applied to validate the quality attributes of the confirmation experiments.

$$CI = \sqrt{F_{\alpha:1;V2} \cdot \mathrm{V}_e \cdot \left(\frac{1}{\eta_{eff}} + \frac{1}{r}\right)} \quad (5)$$

where $F_{\alpha:1;V2}$ represents the value obtained after value F is determined (tabular value at the required level of confidence), V_2 represents the total degree of freedom of variance error, V_e represents the total error variance, r represents the number of repetitions, and η_{eff} represents the number of effective measured results. In this work, the confirmation test ($r = 1$) was used to evaluate the performance of the experimental repetitions for a specified wear rate under ideal conditions. On the basis of the obtained values and the corresponding table, values for $\alpha = 0.05$ and $V_2 = 6$ were calculated. The obtained result for $F_{\alpha:1;V2}$ is 7.71 at a confidence level of 95%. The confidence interval was determined using Equation (5) and has a value of 1.45875. Thus, with a 95% confidence interval of 1.0542-1.156 dB or 0.345 to 4.672 dB, the findings of the experiment verification for the wear rate are predicted to be within the confidence interval of -1.0542 ± 1.156 dB or from 0.345 to 4.672 dB. The wear rate falls within the established confidence interval. Thus, employing approaches with a significance level of 0.05, the system optimization for specified wear rate was achieved. The experimental value of the wear rate for a particular factor combination of *A3, B1*, and *C3* is 3.502 mm^3/km, which falls within the confidence interval of the conformation tests.

CONCLUSIONS

The Taguchi design method is very convenient for statistical analysis of the wear rate of zinc-27aluminum alloy-based hybrid composites reinforced with silicon carbide and TiB_2 particles, according to the extensive analysis. In addition, based on experimental and statistical research, the following conclusions can be drawn:

For all the studied materials, the wear process evolves in the same fashion. The zinc-27aluminum/ 5% SiC/10% TiB_2 hybrid composites outperformed the zinc-27aluminum/5%SiC/5% TiB_2 and zinc-27 aluminum/5% SiC/0% TiB_2 composites in terms of wear resistance and COF.

Because of its simple, methodical, and effective technique for optimising wear test parameters, the Taguchi design method is suited for analysing the wear rate and COF.

The wear rate is influenced the most by TiB_2 content (65.06%), followed by sliding speed (21.51%), and load (13.28%)

The combination of elements *A3*, *B1*, and *C3* yields the lowest wear rate. This result is within the confidence interval of the confirmation test.

The predicted S/N ratio was computed using the best testing parameters for the wear rate and COF, and the 99.5 % confidence level demonstrated good agreement between the predicted and observed wear rates.

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