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Research Article

Dry Sliding Wear Behavior of Copper Matrix Composites Enhanced with TiO_2 and MoS_2 Hybrids

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The paper deals with the properties of copper-based composites. Copper is contributing to the field of automobiles and aerospace industries. The tribological properties of copper are not found to be satisfactory, which may be attributed to the support of producing copper matrix composites with extensive investigations into their properties. Coper-based hybrid composites were fabricated by reinforcing titanium dioxide (TiO_2) and molybdenum disulphide (MoS_2) to enhance the wear and mechanical properties of copper composites. Three specimens were prepared by powder metallurgy process with the designations of Cu + 5wt.%TiO_2, Cu + 5wt.%TiO_2 + 2wt.% MoS_2, and Cu + 5wt.% TiO_2 + 4wt.% MoS_2. The metallurgical analysis was done on the specimens using X-ray diffraction (XRD) analysis which confirms the presence and distribution of Cu, TiO_2, and MoS_2 particles in the specimens. The wear rate was studied on the specimens concerning the sliding velocity, load, and MoS_2 content. The statistical analysis and Taguchi analysis highlight the influencing parameters on the wear rate of the material. Linear regression equations were developed to predict the wear rate using DoE. Through this analysis, the sliding velocity of 3 m/s, a load of 30 N, and a 4% addition of MoS_2 were identified as the optimum parameters for the minimal wear rate. The wear mechanism was analyzed using scanning electron microscopy techniques to reveal the adhesion, delamination, and oxidation.

1. Introduction

Composites based on the metal matrix were produced in the 1970s with fibre reinforcements [1]. In metals, copper has individuality when compared to others, owing to properties such as higher ductility and higher electrical and thermal conductivities [2]. Because of its outstanding properties, it is widely used in electrical equipment subjected to sliding contact [3], with wear resistance being the most important property required for those applications [4]. To improve the properties of pure copper, reinforcements were added to that and copper-based composites were manufactured [5]. Powder metallurgy is the most promising technique to synthesize the composite economically [5]. Though plenty of reinforcements were available, titanium dioxide is the one that can resist wear and corrosion [6] and molybdenum disulphide is the lubricant that helps to reduce the frictional effects [7]. Studies on the TiO_2 and graphite-reinforced copper composites were done and found that the addition of reinforcement improved the workability behavior and the strength coefficient [2, 8]. Investigations into the electrical and mechanical properties of copper composites with nanotitanium dioxide were done, and the outcome of the addition of 1.72 volume percentage showed higher yield strength with electrical conductivity [9]. Pavendhan et al. [10] fabricated the Al 7075 and hybrid aluminium metal matrix composite reinforced with the hard ceramic (10wt % SiC) and soft solid lubricant (3wt% of MoS_2) by the stir-casting method and investigated the friction and wear characteristics. Similarly, investigations into the copper composite with titanium dioxide and polyacrylate reinforcement found improved electrical conductivities [11]. Investigations into the electrical and mechanical properties of copper composites with graphene were done, and the outcome showed that the addition of graphene improved the electrical conductivities and strength in tension and compression [12]. Investigations into the tribology of copper composites with molybdenum disulphide have been conducted, and the outcome shows that the addition of molybdenum disulphide improves wear resistance [13]. Investigations into the tribology of copper composites with carbon nanotubes have been conducted, and the outcome shows that the addition of carbon nanotubes enhanced the wear resistance [14]. Investigations into the tribology of copper composites with graphene have been conducted, and the outcome shows that the addition of graphene enhanced the wear resistance [15]. The addition of silicon carbide (SiC) particles in the copper composites reduces the wear rate of the material concerning sliding velocity and load [16]. 4% addition of fly ash along with SiC increases the hardness, tensile strength, and wear resistance of the copper-based material [17]. Kumar et al. [18, 19] reviewed on the mechanical and thermal properties of for structural applications of graphene hybrid polymer nanocomposites and extended it for effects of various functional groups. Yadav et al. [20] studied on dry sliding wear characteristics of natural fibre-reinforced polylactic acid composites for engineering applications. The applications of copper composites and their investigations into tribological performance are perceived based on the literature.

Copper has exceptional properties of high ductility and thermal conductivity, and its applications involve sliding contact such as electrical equipment and components. Therefore, it is motivated to develop copper-based composites with higher wear resistance to extend the life span and reliability. Through literature review, it is identified that many copper-based composites were developed using various reinforcements to increase the wear resistance, but there remains a gap in studying the combined effects of TiO_2 and MoS_2. To cover the gap, an attempt has been made to achieve the primary objective of developing copper-based materials with high wear resistance and mechanical properties using the reinforcements of TiO_2 and MoS_2. The systematic approach of the addition of TiO_2 and MoS_2 has been followed for the fabrication and characterization. The addition of both reinforcements in the copper matrix is the uniqueness of this study. The systematic approach of analysis such as statistical analysis, Taguchi analysis, and microscopic analysis for various proportions of the reinforcements enhances the accuracy of achieving the objective.

2. Experimentation

Hybrid composites were synthesized with the matrix copper and hardener reinforcement titanium dioxide and softener reinforcement molybdenum disulphide (MoS_2). Both powders of matrix material and reinforcement material were weighed and blended in the essential quantities to accomplish the composites of proportions of Cu with 5wt.%TiO_2; Cu with 5wt.%TiO_2 and 2wt.%MoS_2; and Cu with 5wt.% TiO_2 and 4wt.% MoS_2 based on literature [2]. Blending was performed at a ball-to-powder ratio of 10 : 1 using steel balls in a ball mill for a period of 15 hours at a speed of 300 rpm [2]. Green compacts were compacted in a universal tensile testing machine before being sintered in an electric furnace at 950°C for 2 hours in an argon atmosphere. It is sectioned, mounted, ground, and polished as per the standards for metallographic analysis such as X-ray diffraction analysis and scanning electron microscope along with energy dispersive spectroscopy. The pins, with dimensions of 6×6 mm, were machined from sintered composites using electric discharge machining, and the ends were polished. The wear test is done as per the ASTM standard (ASTM G99) on the dry sliding wear-testing machine.

Based on the literature, parameters were identified and the experimental design was designed with Taguchi's approach as shown in Table 1. With the 0.0001 g accuracy weighing balance, the mass of the samples was measured and logged before and after each run. With the measurements, mass loss was found and the wear rate (K) was calculated based on the standard equation (1) and is listed in Table 1.

$$K = \frac{V}{d}, \qquad (1)$$

where V is the volume (mm^3) of material removed and d is total sliding distance (m).

3. Results and Discussion

3.1. Metallurgical Analysis. With the X-ray diffraction analysis results as shown in Figure 1, the peaks corresponding to copper, titanium dioxide, and molybdenum disulphide were identified, which also confirms that there was no identification of other relevant peaks.

The microscopic image of copper composites is shown in Figure 2(a), and the elemental mapping of the corresponding image is shown in Figures 2(b)–2(d). The presence of copper and its distribution in the composite is shown in Figure 2(b). The elemental maps of titanium (points in green color) and oxygen (points in red color), which were embedded together, are shown in Figure 2(c) for better understanding. Similarly, the elemental mapping of molybdenum (points in green color) and sulphur (points in red color) is shown in Figure 2(d). Thus, the elemental mapping discloses the presence of each element and also shows the reinforcement's distribution in the copper.

Table 1: Experimental design with the wear rate.

Molybdenum percentage	Load (N)	Sliding velocity (m/s)	Wear rate (mm^3/m)
0	10	1	0.003703
0	20	2	0.002545
0	30	3	0.001555
2	10	2	0.002678
2	20	3	0.001373
2	30	1	0.002707
4	10	3	0.000922
4	20	1	0.002918
4	30	2	0.001973

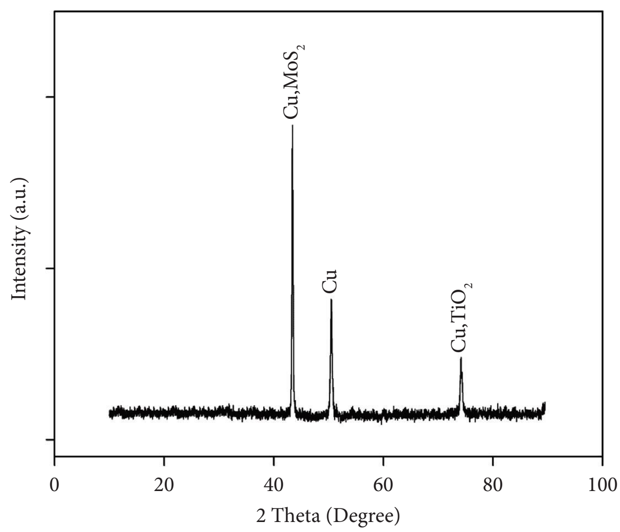


Figure 1: X-ray diffraction analysis of the copper composite.

3.2. Effect of Sliding Velocity on the Wear Rate. The Taguchi method divides all problems into two categories as STATIC or DYNAMIC. While the dynamic problems have a signal factor, the static problems do not have any signal factor. In static problems, the optimization is achieved by using 3 signal-to-noise ratios, i.e., smaller-the-better, larger-the-better, and nominal-the-best. The sliding velocity was considered as the determining factor in the wear rate through the response table and analysis of variance.

Higher delta values of 7.81 were possessed by the sliding velocity in Table 2, and a higher contribution factor of 26.44 was possessed by the sliding velocity in Table 3. The sliding velocity influences the wear rate of materials. The higher sliding velocity leads to increasing the contact forces and temperatures between the contact surfaces which lead to increase in the wear rate. So, the optimum sliding velocity may be taken as 30 m/s as per the investigation.

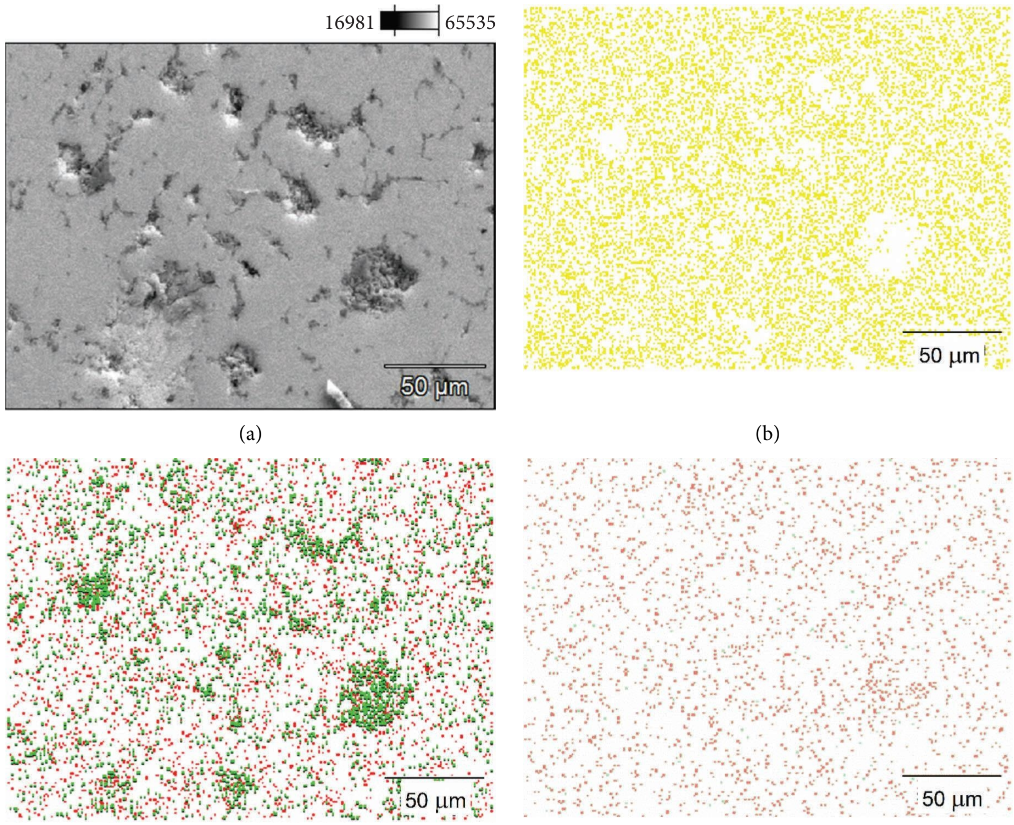
3.3. The Effect of Load on Wear Rate. Generally, the wear rate increases with respect to the amount of load because the load has an impact on the wear rate of any material. From the analysis, it was observed that the load has the least significance on the wear rate when compared with the other parameters, sliding velocity, and molybdenum disulphide addition. The reason for this is that though the load has a considerable effect on the wear rate, the addition of molybdenum disulphide and the increase in the sliding effect have a larger effect on the wear rate by means of acting as a lubricant and with the protection by oxide layers, respectively.

3.4. Effect of Molybdenum Disulphide Addition on the Wear Rate. The addition of molybdenum disulphide has an impact on the wear rate next to the sliding velocity. The delta value and the contribution factor were found to be 2.94 and 3.44, respectively, from the analysis of variance and response table. With the addition of molybdenum disulphide, the wear rate has been reduced as observed from the contour plots, and this is due to the property of self-lubricant possessed by the molybdenum disulphide. MoS_2 has the inherent lubricating properties. The reinforcement of MoS_2 creates the solid lubricant layer over the sliding interface also, which restricts the metal to metal contact and preventing loss of material due to adhesion and abrasion.

3.5. Effect of Parameter Interaction. The interaction plot (Figure 3) shows the combined effect of parameters on the rate of wear. The addition of molybdenum disulphide was found to be significant at higher levels of the load and similar at lower levels of sliding velocity. Interactions between the sliding velocity and the load show their significance at higher sliding velocity.

3.6. The Best Parameter. The best parameters to achieve the minimum wear rate were observed to be 4% of molybdenum disulphide, 3 m/s of sliding velocity, and 30 N of the load as shown in Figure 4. Furthermore, it was observed that the sliding velocity was found to be the most influencing factor from the main effect plot with the highest value of mean.

3.7. Prediction of the Wear Rate. The contour plot predicts the dependency among the variables and predictors in the graphical form and also helps to visualize the value of responses with the change in the variables. Figures 5(a)–5(c) shows the contour plot for the rate of wear with respect to the load and sliding velocity, molybdenum disulphide percentage and sliding velocity, and molybdenum disulphide percentage and load. When higher sliding velocity was combined with lower loads, the rate of wear was lower, whereas when lower sliding velocity was combined with lower loads, the rate of wear was higher (see Figure 5(a)). The lower rate of wear was observed when the higher sliding velocity was combined with a higher molybdenum disulphide percentage, whereas a higher rate of wear was observed when the lower sliding velocity was combined with a lower molybdenum disulphide percentage. A lower wear rate was obtained when lower loads were combined with a higher molybdenum disulphide percentage, whereas a higher wear rate was obtained when lower loads were combined with a lower molybdenum disulphide percentage.



(a) (b) (c) (d)

Figure 2: SEM image of the copper composite with elemental mapping. (a) Cu-5 wt.% TiO_2-4 wt.% MoS_2. (b) Cu. (c) TiO_2. (d) MoS_2.

Table 2: Response table for signal-to-noise ratios (smaller is better).

Levels	Molybdenum percentage	Load	Sliding velocity
1	52.23	53.59	50.23
2	53.35	53.28	52.48
3	55.17	53.87	58.04
Delta	2.94	0.59	7.81
Rank	2	3	1

Table 3: Analysis of variance for the wear rate.

Parameters	DF	Seq SS	Adj SS	Adj MS	F	P	P%
Molybdenum percentage	2	0.0000007	0.0000007	0.0000003	3.44	0.225	11.48
Load (N)	2	0.0000002	0.0000002	0.0000001	0.99	0.501	3.28
Sliding velocity (m/s)	2	0.0000051	0.0000051	0.0000025	26.44	0.036	83.61
Total	8	0.0000061					

$S = 0.000310028$, R-Sq = 96.86%, R-Sq (adj) = 87.45%.

Mathematical correlation amidst the variables and the response wear rate was envisioned with the help of general linear regression. The following equation shows the mathematical correlation for the wear rate response.

$$\text{Wear rate} = 0.00477707 - 0.000165835 \times \text{molybdenum disulphide percentage} - 1.7801e^{-005} \times \text{load} - 0.0009129 \times \text{sliding velocity}. \tag{2}$$

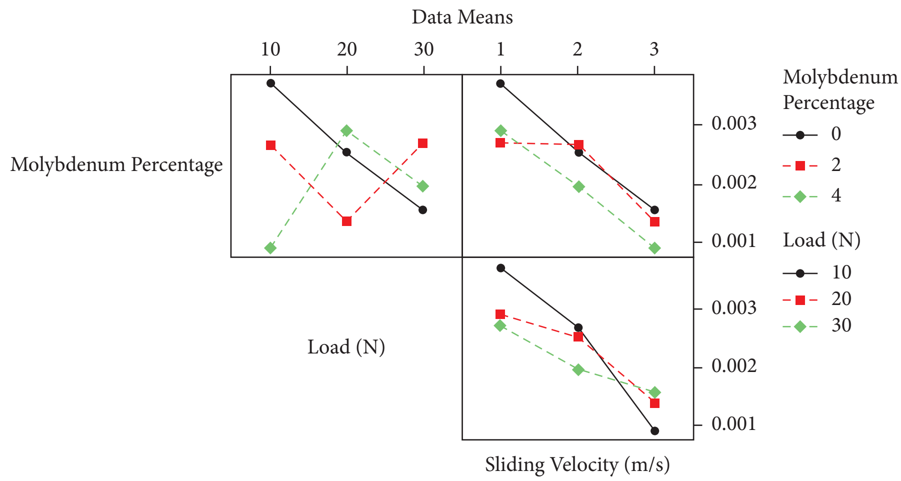


Figure 3: Interaction plot for the wear rate.

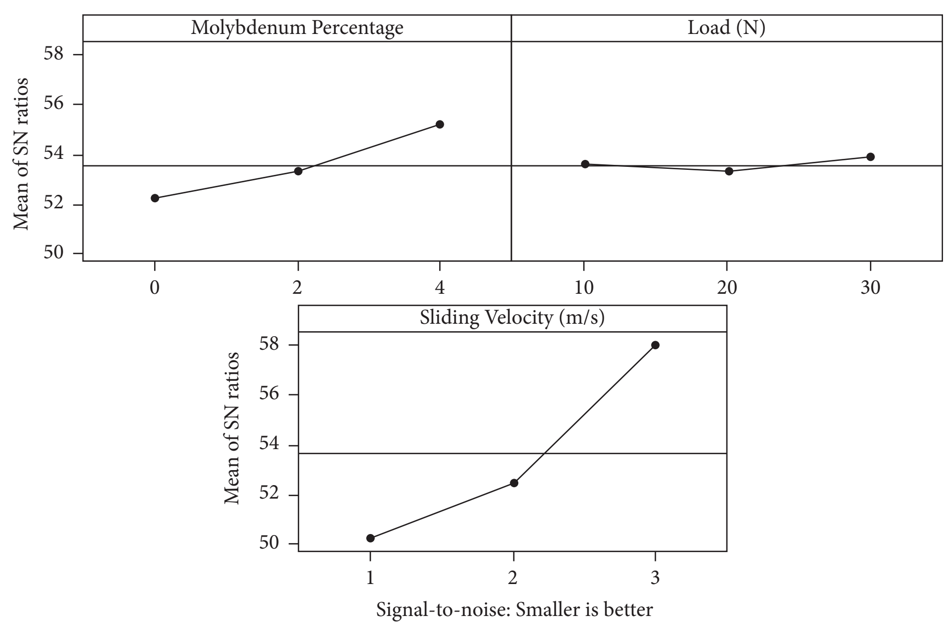


Figure 4: The effect of the wear rate on parameters.

3.8. Validation of the Experiments. The experimentation on the analysis of the wear rate was validated with the confirmation test and the normal probability plot. From the best parameter combination, the predicted value of the wear rate was found to be 0.0007718 and from the confirmation test, the value of the wear rate was found to be 0.000804. The percentage of error was found to be 4.17, which appears to be very low. Along with this, the normal probability plot (Figure 6) also shows that the experimental data lie within the limits and follow the straight line.

3.9. Wear Mechanism. After the wear test, the worn pin surface, which results in the best and worst condition, has been sectioned and investigated through the scanning electron microscope to study the wear mechanism. The worn surface for the worst conditions of wear rate, i.e., the lower load, lower sliding velocity, and no molybdenum disulphide addition, is shown in Figure 7 with the incidence of furrows formed in a row which fallouts the adhesion mechanism [21]. The reason is that at lower sliding velocities, the time taken to complete the required sliding distance is higher when compared with the others and also, the force acting on the pin leads to the generation of heat, which results in the deformation of materials on the pin surface. The worn surface for the best conditions of wear rate, i.e., the higher load, higher velocity, and higher molybdenum disulphide addition, is shown in Figure 8 with the incidence of shallow craters

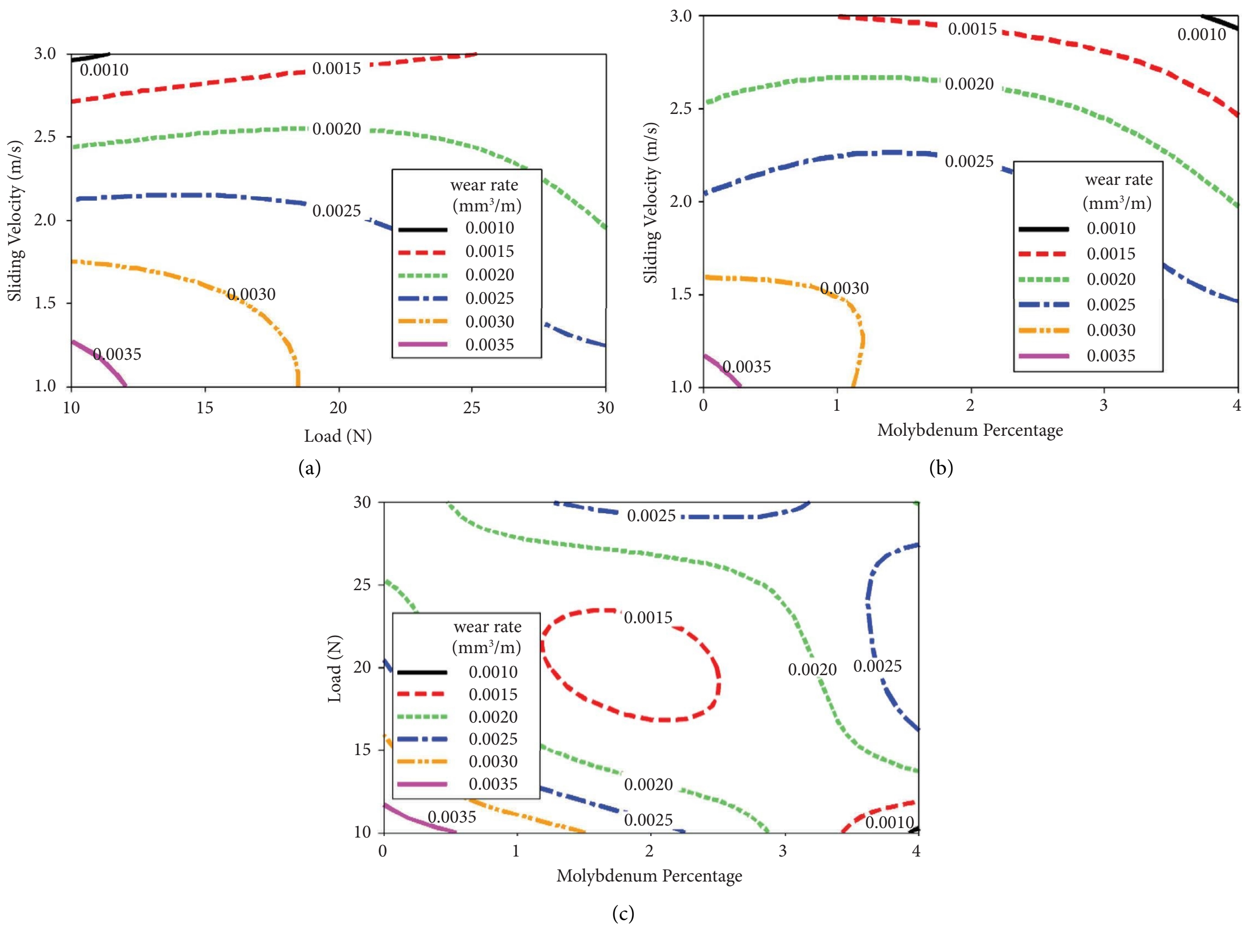


Figure 5: Contour plot for the wear rate.

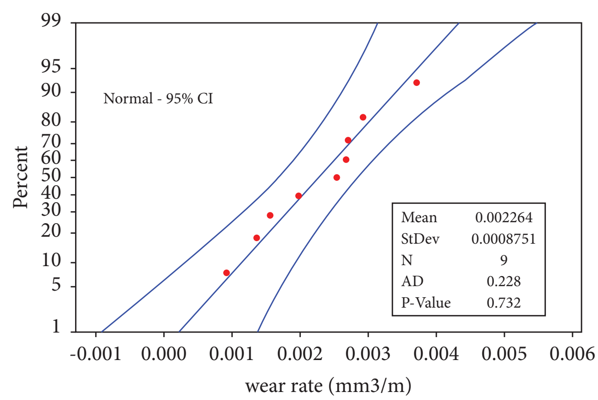


Figure 6: Normal probability plot.

and the fine powders of debris which falls out from the delamination and oxidation mechanism as observed elsewhere [22, 23].

Though the input parameter combinations are higher, the wear rate is found to be lower. One is due to the higher content of molybdenum disulphide, which has a lubricating

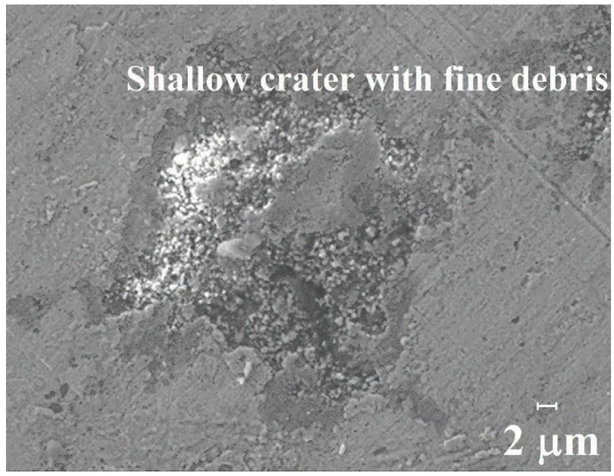


Figure 7: SEM image of the worn surface: adhesion mechanism.

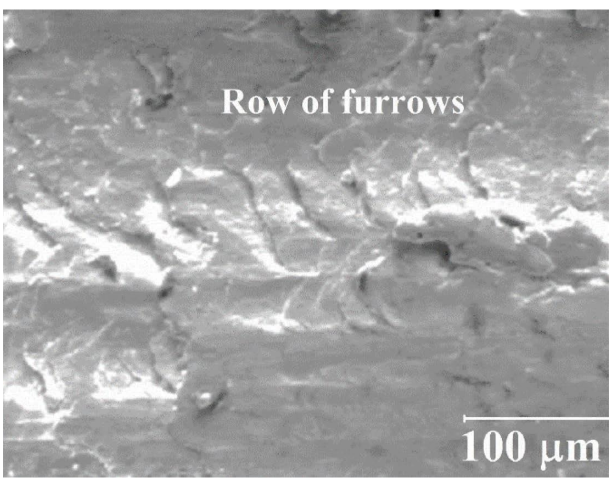


Figure 8: SEM image of the worn surface: delamination and oxidation.

property, and the other is due to the formation of oxides at higher velocities. The increase in the oxygen content is also confirmed in the energy dispersion analysis.

4. Conclusion

Cu-5 weight percent TiO_2, Cu-5 weight percent TiO_2-2 weight percent MoS_2, and Cu-5 weight percent TiO_2-4 weight percent MoS_2 hybrid composites were successfully formulated. Metallographic analysis by X-ray diffraction and elemental mapping endorses the existence of the reinforcement and its dissemination. With Taguchi's design of experiments, the wear tests were conducted and analyzed statistically. The effect of the input factors on the response wear rate was investigated, and it was discovered that the sliding velocity is the most convincing factor on the wear rate. The best parameters for achieving the lowest wear rate were 4 percent molybdenum disulfide, 30 N of the load, and 3 m/s of sliding velocity. Linear regression was developed to envision the wear rate.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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