Parametric Optimization of Wear Characteristics in Bronze-Based Hybrid Composites

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Abstract - **The use of metallic composite materials in tribological applications is growing because of their beneficial qualities, which include a low wear rate and a high strength-to-weight ratio. The tribological behavior of hybrid metallic composite materials reinforced with cobalt and chromium and based on bronze is investigated in this work. Using the powder metallurgy process, cobalt and chromium metal powders, each with a 40µm particle size, were added to a bronze matrix at weight percentages of 2.5, 5.0, and 7.5. A pin-on-disc machine was used to perform sliding wear testing on the manufactured composite specimens in accordance with ASTM G99 guidelines. The Taguchi technique was used to construct the tests, and an analysis of variance (ANOVA) was used to assess how wear parameters, including sliding speed, reinforcement %, applied stress, and sliding distance, affected wear resistance. Multiple linear regression analysis and the Signal-to-Noise ratio approach were used to further examine the composites' wear behavior. The findings show that the tribological performance of hybrid metal matrix composites based on bronze is improved by adding cobalt and chromium as reinforcing components.**

Keywords: Bronze, Cobalt, Chromium, Powder Metallurgy, Wear, ANOVA, Taguchi Method.

I. INTRODUCTION:

Bearings are essential components used to reduce friction between moving parts. The two main types commonly used in machinery are hydrodynamic journal bearings and anti-friction (rolling element) bearings. Their primary function is to support loads between the rotating shaft and the housing, thereby minimizing wear and ensuring smooth operation. Bearings are present in countless everyday applications, ranging from wristwatches and automobiles to computer disk drives. In industrial applications, journal bearings are particularly suited for rotating machinery operating at both low and high speeds. Copper alloys have long been used for bearing because of their combination of moderate-to-high strength, corrosion resistance and self-lubrication properties. [1] Among copper alloys, bronzes have been widely used as bulk material or as coating of steel pieces for applications as bearings, shafts or hydraulic pumps.[2]

Addition of alumina in aluminium bronze composite [3] has shown enhancement in hardness and tribological properties. An addition of alumina in Cu–Sn bronze [4] has shown improvement in the wear rate. The incorporation of nano-ceramic reinforced bronze [5] has enhanced performance in terms of microhardness and sliding wear.

An addition of Cr and Ag [6] in bronze composite has shown improvement in the wear resistance and lubricating properties of the composites simultaneously. An addition of SiC, SiO2 and graphite [7] in bronze composite has shown improvement in corrosion resistance under acid rain.

Wear and friction behavior of composites based on bronze have remains insufficiently explored, especially in relation to hybrid composites reinforced with cobalt and chromium. Furthermore, not enough information is now accessible on these materials, and prior research has not given much attention to the mechanisms underlying tribological property loss. Consequently, the results of current research are quite conservative. Powdered cobalt and chromium metals were added to a bronze matrix in this study at weight percentages of 2.5, 5.0, and 7.5. The Taguchi design of trials was used to assess the tribological characteristics, specifically sliding wear resistance. Additionally, an ANOVA was performed to ascertain the percentage impact of each element on the composites' dry sliding wear behavior.

II. TAGUCHI TECHNIQUE:

A very useful tool for creating high-quality systems is the Taguchi approach. It provides a straightforward, effective, and methodical way to optimize designs for cost, quality, and performance. This approach is especially helpful when working with discrete design parameters and qualitative data. Taguchi parameter design minimizes susceptibility to changes in system performance while improving performance features through design parameter adjustments. This method follows a systematic, multi-stage approach and a structured set of experiments to gain comprehensive understanding of a product or process performance. The experimental design process consists of three main phases: planning, execution, and analysis with interpretation. Among these, the planning phase is the most critical and requires maximum attention. Data obtained from each experiment are analyzed to assess the influence of various design parameters.

ANOVA is a statistical technique used to evaluate experimental data based on the least squares approach. It determines meaningful outcomes by analyzing the variance and the mean effects of different design parameters.

III. EXPERIMENTATION:

A. Material Description

In the current research, the composite was fabricated using bronze powder (40 µm) as the matrix and cobalt and chromium metal powders (40 µm) as reinforcement materials.

B. Manufacturing Process

For fabrication in this investigation, the powder metallurgy approach was used. The powdered chromium, cobalt, and bronze used as starting materials were 99% pure. Cobalt and chromium powders at weight percentages of 2.5, 5.0, and 7.5 were used to reinforce metallic composites based on bronze. To guarantee even distribution, a mechanical stirrer was used to fully mix these particles.

After that, the mixed composite powders were put into a die that measured 25 mm in length and 8 mm in diameter. Green compacted specimens were produced by cold compaction of the powder mixes in a punch-die assembly under a hydraulic force of 75 kN using a Universal Testing Machine. The green compacted specimens were sintered with argon gas in a regulated vacuum chamber to stop chemical reactions during processing. At least one component powder's melting point was maintained below the sintering temperature. The samples were heated to 700°C in 60 minutes at a regulated rate of 120°C per minute. After being kept at this temperature for seven hours, they were progressively cooled over the course of three hours to room temperature. The composition of the manufactured composites is shown in Table 1.

TABLE I. COMPOSITION OF FABRICATED COMPOSITES

Material Composition	Bronze (Wt.%)	Cobalt (Wt.%)	Chromium (Wt.%)
Composite 1	95	2.5	2.5
Composite 2	90	5.0	5.0
Composite 3	85	7.5	7.5

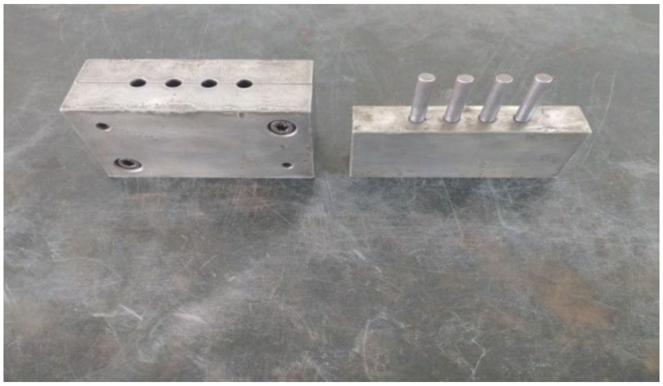


Fig. 1. Punch and Die

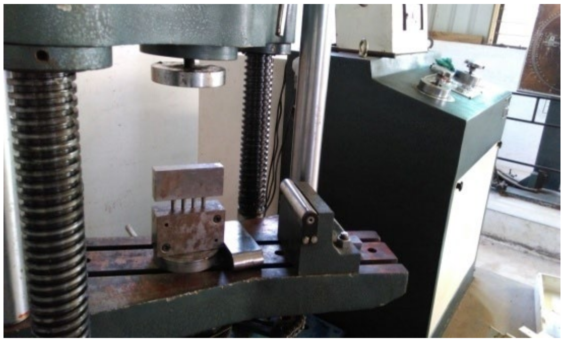


Fig. 2. Loading in UTM

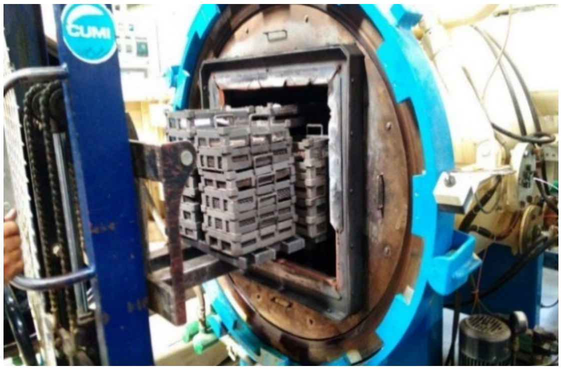


Fig. 3. Sintering Atmosphere

C. Optimized Experimental Design

The experiments were designed using a standard orthogonal array approach. The selected orthogonal array was required to have degrees of freedom equal to or greater than the total degrees of freedom of the chosen wear parameters. For this investigation, an L27 orthogonal array was employed to design the experiments. The primary wear parameters selected for evaluation were: (i) material composition, (ii) applied load, (iii) sliding distance, and (iv) sliding speed.

Material loss was selected as the response variable in this investigation. The process parameters and their three respective levels are summarized in Table 2. In addition, the wear test data were subjected to analysis of variance (ANOVA) to determine the statistical significance of the various factors.

TABLE II. PROCESS PARAMETER SELECTION AT THREE LEVELS

Control Factors	Units	Level 1	Level 2	Level 3
M: Material Composition	Wt.%	2.5	5.0	7.5
L: Load	kg	1	2	3
S: Speed	rps	3.33	6.66	10
D: Sliding Distance	km	1	2	3

D. Wear Test

The dry sliding wear behavior of the composite was assessed using a pin-on-disc testing machine as per ASTM G99 specifications. Before conducting the test, the sintered specimens (8 mm diameter and 25 mm height) were cleaned with acetone and properly dried. Each specimen's initial mass was then recorded using a single-pan electronic balance with a precision of 0.0001 g.

During experimentation, the specimen was held against a rotating EN32 steel disc with a hardness of 65 HRC under an applied load. Once the specified sliding distance was reached, the specimens were removed, cleaned with acetone, dried, and weighed again to evaluate the material loss due to wear. The dry sliding wear was calculated from the difference between the initial and final weights of the specimen. The investigation examined the influence of sliding speed, sliding distance, and applied load on wear behavior.

IV. RESULTS & DISCUSSIONS:

A. Statistical Analysis:

To analyze the effects of material composition (M), load (L), sliding speed (S), and sliding distance (D) on wear characteristics, experiments were organized using an L27 orthogonal design. The dry sliding wear results obtained from different parameter combinations are listed in Table 3, including material loss, S/N ratio, and mean response data.

According to the response table (Table 4), applied load was found to be the most influential parameter on material loss during sliding wear, followed in order by sliding distance, sliding speed, and material composition. Analysis of variance (ANOVA) was performed to statistically assess the significance of these design factors on wear performance. The results of ANOVA were also used to determine the optimum combination of process parameters. The statistical analysis was conducted at a 5% level of significance, ensuring a 95% confidence level.

Table 5 presents a summary of the ANOVA results. Figure 4 provides a graphical representation of the effects of the control factors on material loss and identifies the optimal conditions for reducing sliding wear: 2.5% material composition (level 1), 3 kg applied load (level 3), 600 rpm sliding speed (level 3), and 3000 m sliding distance (level 3). The last column of Table 5 shows the percentage contribution (P) of each parameter to the total variation in wear, as determined by the ANOVA for cobalt- and chromium-reinforced bronze-based composites. The results indicate that load has the most significant effect (P = 71.10%), followed by material composition (P = 1.22%), speed (P = 6.35%), and sliding distance (P = 14.95%). The combined error contribution amounts to 6.35%. [8-14}

TABLE III. TAGUCHI L27 ORTHOGONAL ARRAY RESULT FOR MATERIAL LOSS

Material Composition (M)	Load (L)	Speed (S)	Sliding Distance (D)	W1 -W2	SN Ratio (dB)
2.5	1	3.33	1	0.0013	57.72113
2.5	1	6.66	2	0.0021	53.55561
2.5	1	10	3	0.0039	48.17871
2.5	2	3.33	2	0.0048	46.37518
2.5	2	6.66	3	0.0064	43.8764
2.5	2	10	1	0.0051	45.8486
2.5	3	3.33	3	0.0145	36.77264
2.5	3	6.66	1	0.0061	44.2934
2.5	3	10	2	0.0139	37.1397
5	1	3.33	1	0.001	60
5	1	6.66	2	0.0019	54.42493
5	1	10	3	0.0034	49.37042
5	2	3.33	2	0.0041	47.74432
5	2	6.66	3	0.0059	44.58296
5	2	10	1	0.0045	46.93575
5	3	3.33	3	0.0139	37.1397
5	3	6.66	1	0.0056	45.03624
5	3	10	2	0.0125	38.0618
7.5	1	3.33	1	0.0007	63.09804
7.5	1	6.66	2	0.0017	55.39102
7.5	1	10	3	0.0029	50.75204
7.5	2	3.33	2	0.0037	48.63597
7.5	2	6.66	3	0.0049	46.19608
7.5	2	10	1	0.0039	48.17871
7.5	3	3.33	3	0.0129	37.78821
7.5	3	6.66	1	0.0049	46.19608
7.5	3	10	2	0.0119	38.48906

TABLE IV. PERFORMANCE RESPONSE TABLE FOR S/N RATIOS (MATERIAL LOSS: LOWER IS BETTER)

Material Composition (M)	Load (L)	Speed (S)	Sliding Distance (D)
45.97	54.72	48.36	50.81
47.03	46.49	48.17	46.65
48.30	40.10	44.77	43.85
2.33	14.62	3.59	6.96
4	1	3	2

TABLE V. MATERIAL LOSS ANOVA RESULTS

Source	DF	Adj SS	Adj MS	F - Value	P - Value	P (%)
M	2	0.000006	0.000003	1.79	0.195	1.22
L	2	0.000347	0.000174	99.73	0.000	71.10
S	2	0.000031	0.000015	8.89	0.002	6.35
D	2	0.000073	0.000036	20.93	0.000	14.95
Error	18	0.000031	0.00002			6.35
Total	26	0.000488				100

Model Summary:

R-sq = 93.59%

R-sq(adj) = 90.74%

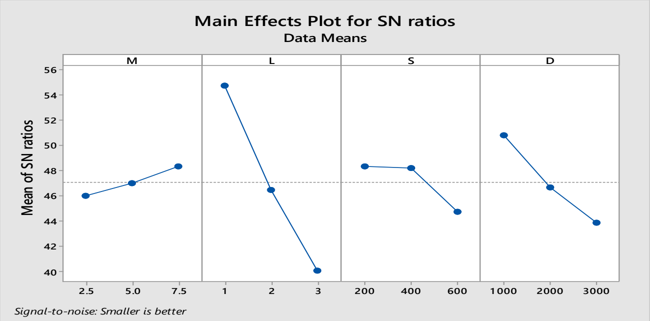
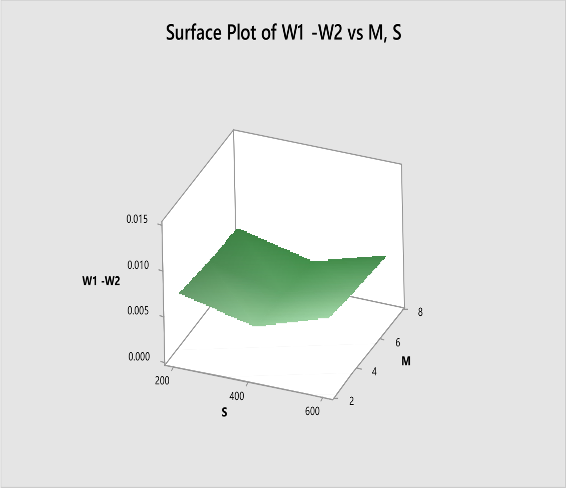
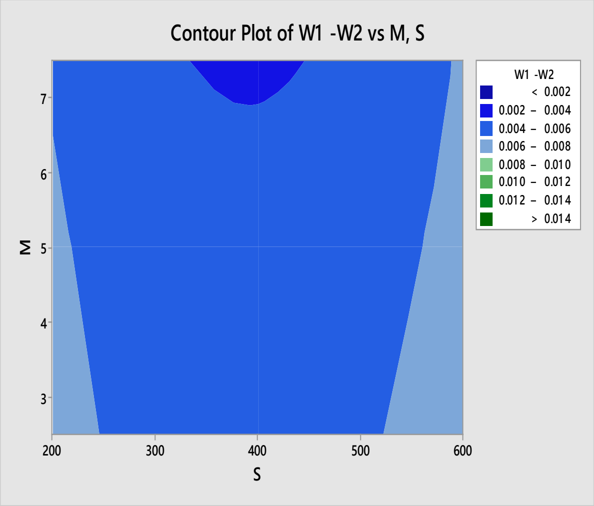


Fig. 4. Main effects plot for S/N ratios – Material loss

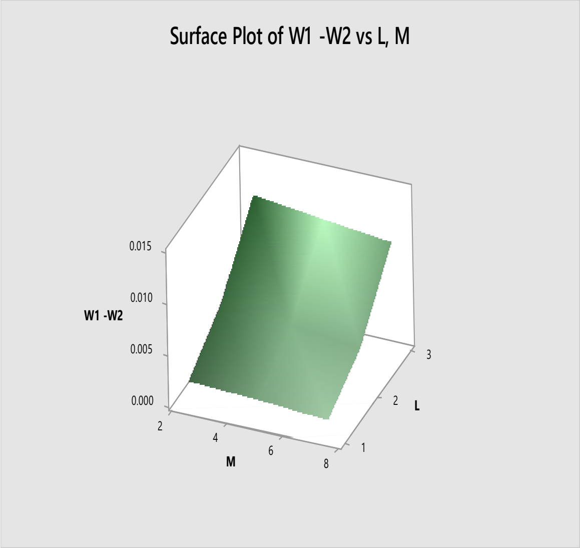


(a)



(b)

Fig. 5. (a) Surface plot for material loss versus material composition and sliding speed. (b) Contour plot for material loss versus material composition and sliding speed.



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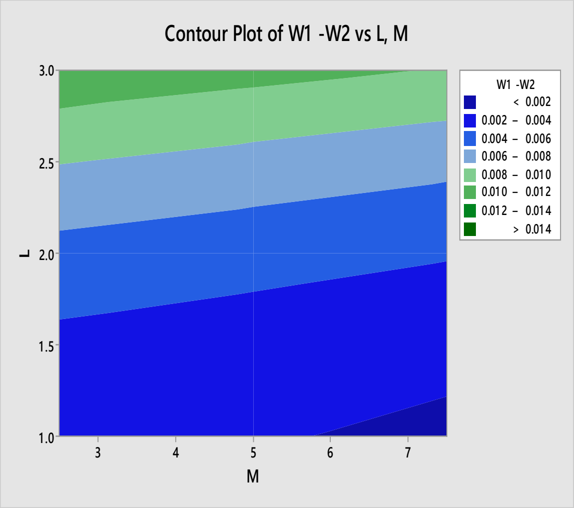

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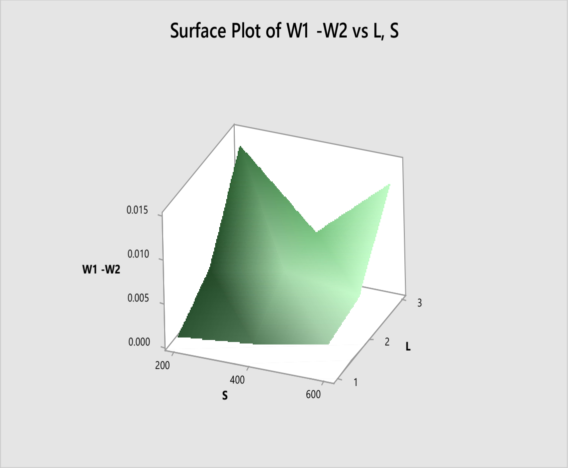
Fig. 6. (a) Surface plot for material loss versus applied load and material composition. (b) Contour plot for material loss versus applied load and material composition.



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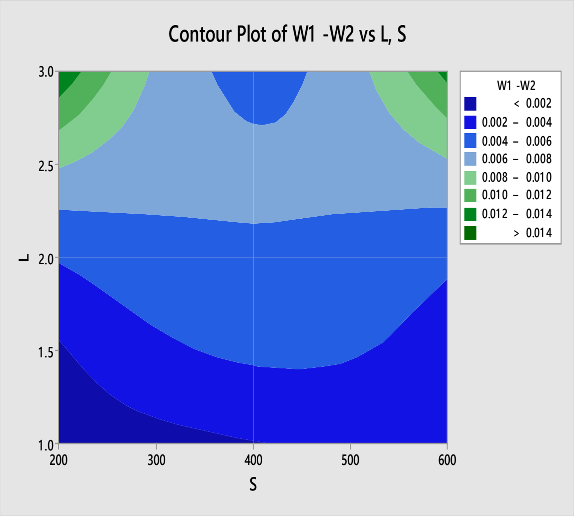


(b)

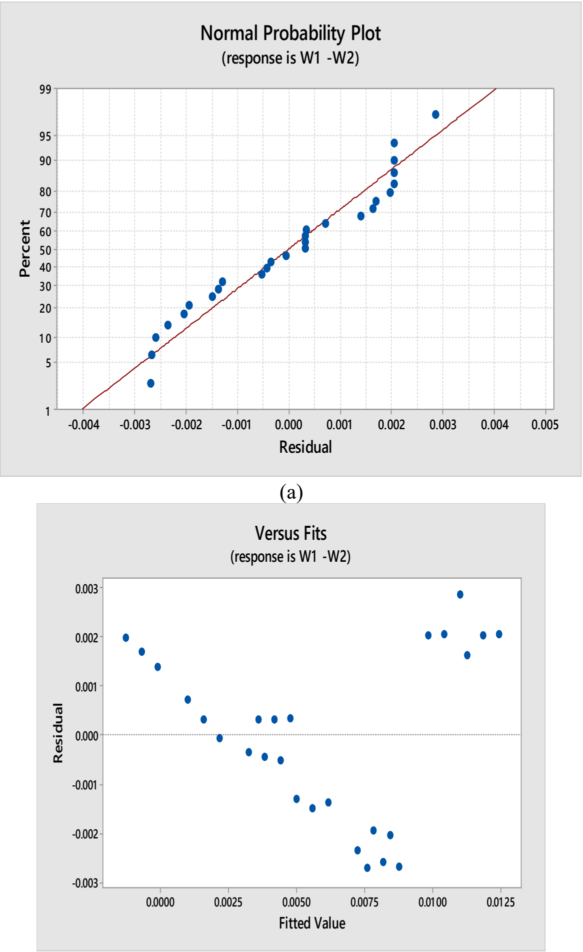
Fig. 7. (a) Surface plot for material loss versus applied load and sliding speed. (b) Contour plot for material loss versus applied load and sliding speed.

B. Multiple linear regression models:

Multiple linear regression models were created using the statistics program MINITAB 17. Based on the observed data, this model creates a linear relationship between the independent variables and the response variable. In accordance with this, the regression equation for material loss was created.

$$W1 - W2 = -0.00607 - 0.000236\,M + 0.004294\,L + 0.000001\,S + 0.000002\,D$$

The residuals' normal probability curve is shown in Figure 9. The plot suggests that the residuals have a normal distribution because the data points closely match the normal probability line. This demonstrates that the model accurately forecasts material loss as a result of sliding wear.



(a)

(b)

Fig. 8. Normal Probability plot of Residuals and Fits a) Normal probability plot of residuals b) Plot of residuals v/s fitted values

C. Wear Mechanism:

The pin and counterface undergo relative motion under the imposed stress when their asperities come into contact. First, contact mostly takes place at the many acute asperities present on both surfaces. These asperities interact to produce either plastic deformation or elastic contact depending on the applied force and sliding speed. With the exception of the partially projecting reinforcing particles, most asperities experience plastic deformation at the contact points due to the acute character of these locations, where the effective stress may surpass the elastic limit. The surface fills the troughs of the pin and counterface as it experiences plastic deformation. Certain asperities may break during this process, producing tiny wear debris from both surfaces. [15-26]

V. CONFIRMATION TEST:

A confirmation experiment was conducted using the optimal parameters listed in Table 6 to verify the obtained results. The outcomes of the confirmation test, which compare the experimental values with those predicted by the regression model, are presented in Table 7. The deviation between the predicted and experimental material loss values ranged from 4.77% to 9.61%. Overall, the difference between the regression model predictions and the experimental results was minimal, indicating good agreement. [27-31]

TABLE VI. MATERIAL LOSS CONFIRMATION STUDY

% Reinforcement (M)	Applied load (L)	Speed (S)	Sliding Distance (D)
2.5	2	8.33	1.5
5.0	2	8.33	1.5
7.5	2	8.33	1.5

TABLE VII. VALIDATION OF MATERIAL LOSS EXPERIMENT AND REGRESSION MODEL COMPARISON

Expt. Material Loss	Reg. model eqn. Material Loss	% Error
0.0057	0.005428	4.77
0.0053	0.004838	8.71
0.0047	0.004248	9.61

VI. CONCLUSIONS:

Bronze-based hybrid composites containing 2.5%, 5.0%, and 7.5% by weight of cobalt and chromium were fabricated through the powder metallurgy route. The tribological performance of the developed composites was evaluated, and the following conclusions were drawn.

1. The process of powder metallurgy was effectively used to create hybrid composites based on bronze reinforced with cobalt and chromium.
2. The hybrid composites based on bronze reinforced with 7.5wt.% cobalt and chromium were found to have the highest wear resistance.
3. Under dry sliding wear circumstances, applied load (71.10%) has the greatest impact on the material loss of the bronze-based hybrid composite, followed by sliding distance (14.95%), sliding speed (6.35%), and material composition (1.22%).
4. A regression equation designed for a hybrid composite made of bronze reinforced with cobalt and chromium has been utilized to accurately forecast material loss under intermediate conditions.
5. The design of experiments using the Taguchi technique is successfully used to explore the tribological characteristics of hybrid composites based on bronze since the results of the confirmation test revealed the test error.

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