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Optimization of wear rate in tungsten-copper metal matrix composites: a robust design approach

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ABSTRACT

Introduction. Wear is a critical factor in assessing the performance and durability of tungsten-copper (*W-Cu*) composites. These composites are widely used in electrical contacts, electrodes, and high-temperature applications. Tungsten provides high hardness and wear resistance, while copper ensures excellent electrical and thermal conductivity. ***The purpose of the work.*** This study aims to quantify the wear rate based on pin mass loss and to develop a statistically robust procedure for minimizing the dry-sliding wear rate of *W-Cu* metal matrix composites. The investigation focuses on determining the optimal process parameters for achieving minimal wear. **The methods of investigation.** In this study, a *Taguchi* L_9 orthogonal array was employed to design the experiments, with the following key parameters: reinforcement percentage (20–40%), temperature (160–200 °C), and load (80–100 N). Wear tests were conducted using a pin-on-disc tribometer. The results were analyzed using the signal-to-noise (*S/N*) ratio approach (smaller-the-better characteristic) and analysis of variance (*ANOVA*). The experiments followed the 'One Variable At A Time' (*OVAT*) principle, varying only one parameter while keeping the others constant. Furthermore, *ANOVA* was used to assess the individual influence of each control factor – reinforcement percentage, temperature, and load – on the wear performance of the *W-Cu* composites. **Results and Discussion.** The experimental results were analyzed using signal-to-noise (*S/N*) ratios (smaller-the-better characteristic) and analysis of variance (*ANOVA*). The optimum parameter combination – 30% reinforcement, 200°C, and 80N – resulted in the lowest wear rate of 3.498×10^{-7} mm³/(N·m). *ANOVA* identified temperature as the most influential factor, contributing 90.6% to the performance variation, followed by reinforcement percentage (7.5%) and load (1.8%). Validation experiments confirmed the prediction accuracy, with an error of 4.6%. This study demonstrates the effectiveness of the *Taguchi* method in identifying a robust set of process parameters for enhancing the wear performance of *W-Cu* composites, offering practical guidance for industrial applications.

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Introduction

The combination of high thermal and electrical conductivity, low thermal expansion, and a high melting point makes tungsten-copper (*W–Cu*) pseudoalloys critical for numerous industrial applications, such as resistance welding electrodes, high-current-density switches, and high-heat-flux thermal management components [1–3]. The service life of these components is often limited by the progressive degradation of the contact surface due to wear, accompanied by increasing electrical contact resistance, leading to premature failure [4, 5]. Consequently, the wear behavior of *W–Cu* pseudoalloys constitutes a complex tribosystem governed by several interdependent factors, primarily: (a) the volume fraction of tungsten reinforcement, (b) the interfacial temperature rise during sliding, and (c) the applied mechanical load.

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These variables collectively govern the formation and stability of the copper-rich tribolayer as well as the integrity of the tungsten skeleton [6, 7].

Conventional one-variable-at-a-time (*OVAT*) studies of *W–Cu* pseudoalloys suggest that increasing the tungsten volume fraction enhances wear resistance but compromises ductility and increases electrical resistance. Elevated temperatures can soften the copper matrix, which may either improve or deteriorate the tribolayer's effectiveness depending on the specific conditions. Higher applied loads intensify subsurface shear stresses, promoting delamination of the tribolayer from the tungsten skeleton. Given the interdependence of these effects, identifying an optimal parameter set for minimizing wear cannot be achieved solely through empirical methods or exhaustive testing.

Taguchi-based robust design methodologies provide a cost-effective approach for optimizing multiple discrete variables while accounting for uncontrollable noise factors [10, 11]. These methodologies employ orthogonal arrays to minimize the number of required experiments, assess robustness via signal-to-noise (***S***/***N***) ratios, and determine the significance of each variable using analysis of variance (*ANOVA*). Thus, *Taguchi* robust design offers a structured framework for optimizing the tribological performance of material systems.

While numerous studies have applied *Taguchi*-based robust design to various tribosystems [12–14], a systematic investigation of the simultaneous effects of tungsten volume fraction, temperature, and load on the sliding wear of liquid-phase sintered *W–Cu* composites is lacking.

Therefore, this study utilizes the *Taguchi* L_9 orthogonal array to identify the variable combination (tungsten volume fraction, temperature, and load) that minimizes the dry-sliding wear rate of liquid-phase sintered *W–Cu* composites. The nine experiments defined by the array were performed on a pin-on-disc tribometer. ***S***/***N*** ratios were calculated using the "smaller-the-better" criterion, and *ANOVA* was applied to quantify the contribution of each independent variable to the wear rate. The optimal condition set identified herein is expected to provide materials scientists and design engineers with statistically validated processing and operational guidelines for developing reliable *W–Cu* contacts [15–20].

Methods

Elemental tungsten (−10 µm, 99.9% purity) and electrolytic copper (−25 µm, 99.8% purity) powders were planetary ball milled to prepare blends with 20, 30, and 40 vol.% of tungsten. Milling was performed for four hours at 200 rpm under an argon atmosphere. The blended powders were then cold-pressed at 350 MPa to produce green compacts (10 mm thick × 20 mm diameter). Subsequently, the compacts were liquid-phase sintered at 1,350 °C for 90 minutes in a flowing dry hydrogen (H_2) atmosphere. After sintering, the samples achieved a final density ≥97% of the theoretical density, as confirmed by *Archimedes*' principle. Light microscopy analysis revealed a fully densified copper matrix with rounded tungsten grains (mean intercept length of approximately 6 µm).

Wear testing was performed on a *Ducom TR-20LE* pin-on-disc tribometer (Fig. 1), compliant with *ASTM G99*. The pseudoalloy pins (6 mm diameter × 12 mm length, ***Ra*** ≈ 0.2 µm) were pressed against hardened *AISI 52100* steel discs (60 HRC, ***Ra*** = 0.1 µm). Tests were conducted under controlled ambient temperature (±2 °C) and humidity. Normal loads of 80, 90, and 100 N were applied, corresponding to an initial *Hertzian* contact pressure of 390–430 MPa. The sliding velocity was set to 0.5 $m \cdot s^{-1}$ over a total sliding distance of 1,500 m. Each wear test was performed in duplicate, with a coefficient of variation below 5%. Prior to testing, both pin and disc surfaces were cleaned with acetone and dried. The wear rate was calculated from the pin's weight loss, measured using a high-precision electronic balance (±0.1 mg). This weight loss was converted to volume loss using the composite's density and then normalized by the applied load and sliding distance to obtain the specific wear rate in units of $mm^3/(N \cdot m)$.

$$\text{Wear rate} = \frac{\Delta m}{\rho \times F \times L}, \tag{1}$$

where $\boldsymbol{\Delta m}$ is the mass loss (g); $\boldsymbol{\rho}$ is the composite density ($g \cdot cm^{-3}$); $\boldsymbol{F}$ is the normal load (N); $\boldsymbol{L}$ is the total sliding distance (m).

Fig. 1. Tribometer setup

Each experimental condition was tested in duplicate to ensure reproducibility, and the mean wear rate was used for subsequent analysis.

Prior to the multi-factor statistical optimization, a preliminary series of *OVAT* experiments was conducted to evaluate the individual effect of each parameter and identify the operational ranges with the greatest influence on wear rate. In the *OVAT* approach, only one variable is varied at a time while all others are held constant. This method facilitated the selection of appropriate factor levels for the subsequent design of experiments (*DOE*).

Results and Discussion

In the initial *OVAT* series, the tungsten volume fraction and temperature were held constant, while the applied load was varied from 60 N to 100 N (Table 1). The wear rate exhibited a nearly linear increase from 3.588×10^{-3} mm³/(N·m). at 60 N to 4.325×10^{-3} mm³/(N·m). at 100 N.

Fig. 2 indicates a significant acceleration in wear within the 80–100 N interval (the wear rate increased from 3.784 to 4.325×10^{-3} mm³/(N·m). This suggests that at loads exceeding 80 N, the composite's load-bearing capacity is compromised due to elevated contact stresses and delamination of the copper matrix. Consequently, the load levels for the *Taguchi* design of experiments (*DOE*) were selected to represent both moderate and severe wear regimes, specifically 80 N, 90 N, and 100 N.

In the second *OVAT* series, temperature was varied from 120 °C to 200 °C while the tungsten volume fraction and applied load were held constant (Table 2). The wear rate decreased from 3.588×10^{-3} mm³/(N·m) at 120 °C to 3.501×10^{-3} mm³/(N·m) at 200 °C. The most pronounced reduction occurred between 160 °C and 200 °C (Fig. 3).

Table 1

***OVAT* experimental design for load variation**

Sr. No.	Reinforcement (%)	Load (N)	Temperature (°C)	Wear rate (mm³/Nm)
1	10	60	120	3.588
2	10	70	120	3.676
3	10	80	120	3.784
4	10	90	120	4.141
5	10	100	120	4.325

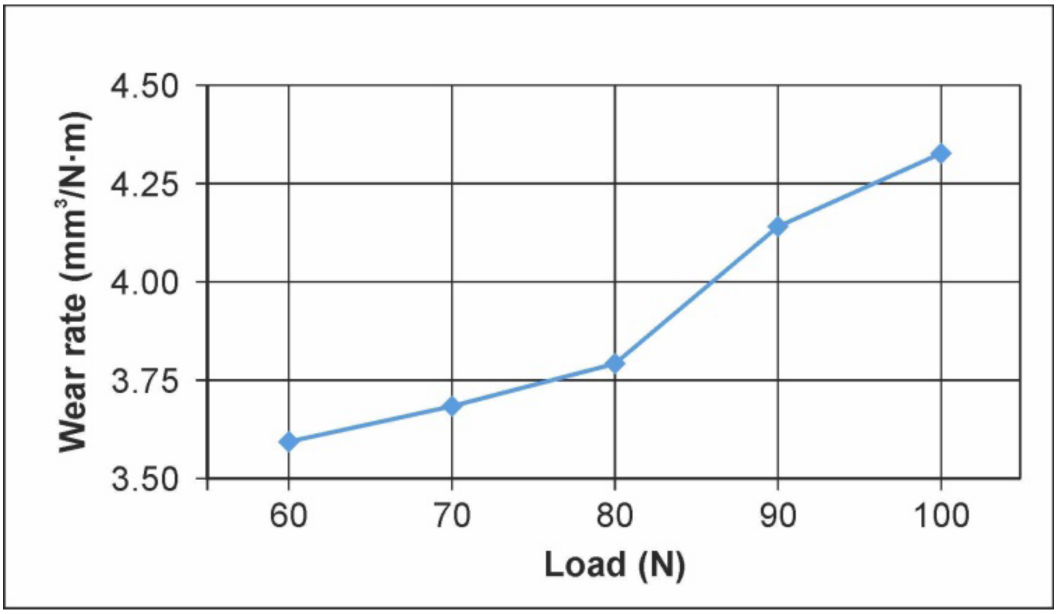

Fig. 2. Wear rate vs load

Table 2

***OVAT* experimental design for temperature variation**

Sr. No.	Reinforcement (%)	Load (N)	Temperature (°C)	Wear rate (mm^3/Nm)
1	10	60	120	3.588
2	10	60	140	3.572
3	10	60	160	3.541
4	10	60	180	3.513
5	10	60	200	3.501

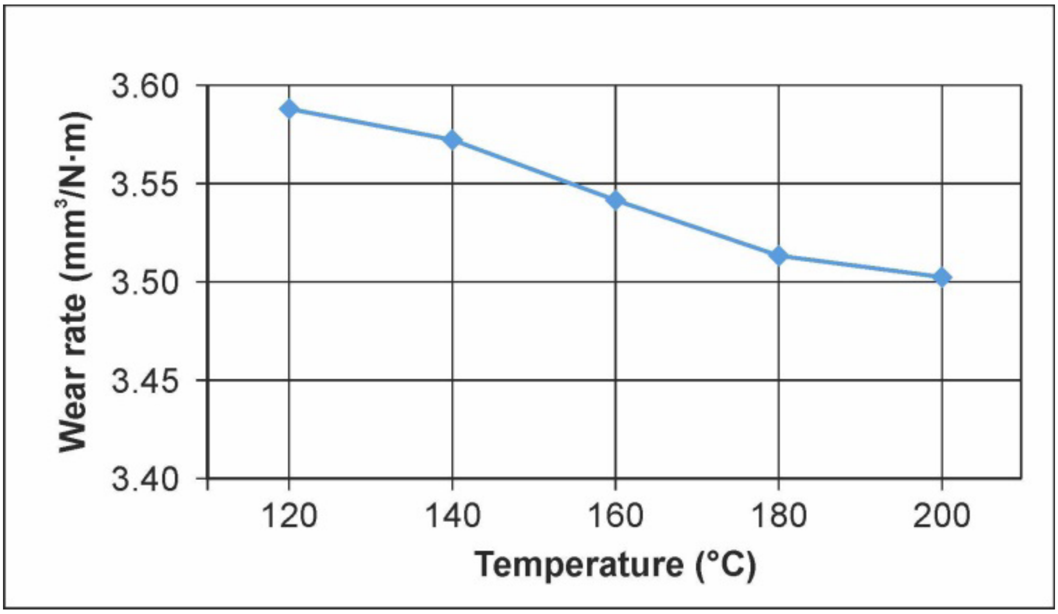

Fig. 3. Wear rate vs temperature

This trend suggests that elevated temperature facilitates the formation of a protective oxide tribolayer, which reduces direct metal-to-metal contact and, consequently, wear. Therefore, the temperature levels selected for the *Taguchi DOE* were 160 °C, 180 °C, and 200 °C, encompassing the range where tribo-oxidative mechanisms become predominant.

In the final *OVAT* series, the tungsten volume fraction was varied while the load and temperature were maintained at 60 N and 120 °C, respectively. This was done to isolate the effect of reinforcement content on wear behavior. The resulting wear rates are shown in Table 3.

Table 3

***OVAT* experimental design for reinforcement variation**

Sr. No.	Reinforcement (%)	Load (N)	Temperature (°C)	Wear rate (mm³/Nm)
1	10	60	120	3.588
2	20	60	120	3.542
3	30	60	120	3.516
4	40	60	120	3.508
5	50	60	120	3.499

Fig. 4 shows a continuous decrease in wear rate with increasing tungsten content. Increasing the tungsten volume fraction from 10% to 50% reduced the wear rate from 3.588×10^{-3} to 3.499×10^{-3} mm³/(N·m), indicating enhanced wear resistance. This improvement can be attributed to the increased presence of the hard tungsten phase, which enhances load-bearing capacity, restricts plastic deformation of the copper matrix, and mitigates micro-cutting and abrasion during sliding. Additionally, the tungsten particles act as barriers to crack propagation, contributing to a more stable tribolayer under the given load and temperature conditions.

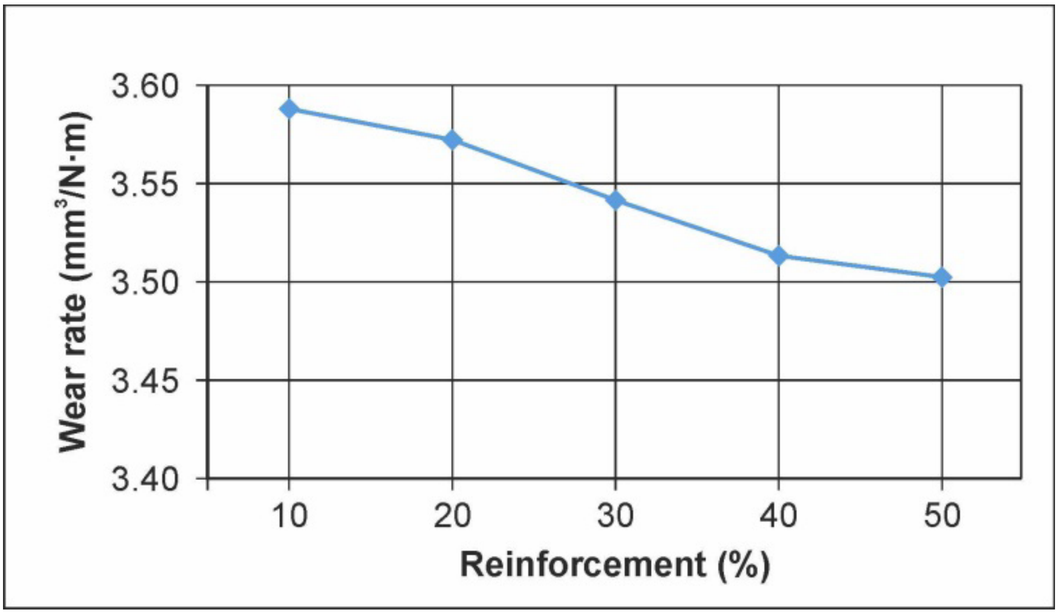

Fig. 4. Wear rate vs reinforcement

The *OVAT* testing confirmed that significant variations in wear rate occur at elevated loads and temperatures. Based on these findings, the input parameters and their levels were finalized, as reported in Table 4.

Following the identification of suitable operational ranges for each parameter, the study employed a *Taguchi* L_9 orthogonal array to analyze the combined effect of tungsten volume fraction, temperature, and load on the wear behavior of *W–Cu* composites. The experimental design matrix, along with the measured wear rate for each run, is presented.

Thus, utilizing the parameter ranges identified via *OVAT* testing, a structured *Taguchi* design of experiments (*DOE*) was implemented to systematically investigate the interaction of these three factors. The nine experiments, designed according to the L_9 orthogonal array, enable a statistically balanced evaluation of factor effects and interactions.

Table 4

Control factors and their levels for the *Taguchi* L_9 orthogonal array

Control factor	Level 1	Level 2	Level 3
Reinforcement (%)	20	30	40
Temperature (°C)	160	180	200
Load (N)	80	90	100

The complete *DOE* matrix, including the experimental wear rates and the calculated signal-to-noise (***S***/***N***) ratios (based on the "smaller-the-better" criterion), is provided in Table 5.

Table 5

***DOE* experimental matrix (*Taguchi* L_9 array) with measured wear rate and corresponding *S*/*N* ratio**

Reinforcement (%)	Temperature (°C)	Load (N)	Wear rate (mm³/(N·m))	*S*/*N* ratio (dB)
20	160	80	4.245	−12.5576
20	180	90	3.593	−11.1091
20	200	100	3.759	−11.5014
30	180	80	3.583	−11.0849
30	200	90	3.575	−11.0655
30	160	100	4.199	−12.4629
40	200	80	3.817	−11.6344
40	160	90	4.310	−12.6895
40	180	100	3.794	−11.5819

The ***S***/***N*** ratio was calculated using the "smaller-the-better" criterion **to** optimize for wear resistance:

$$S\ /\ N = -10\log10\left(1/n\sum_{i=1}^{n} y_i^2\right), \qquad (2)$$

where y_i is the measured wear rate for the ***i***-th trial.

Substantial variation in wear rates was observed across the nine experimental runs, highlighting the process's sensitivity to the input parameters. The specific wear rate ranged from a minimum of 3.575 mm³/(N·m) to a maximum of 4.310 mm³/(N·m), underscoring the need for parameter optimization. These results form the basis for selecting the optimal parameters through subsequent *ANOVA*, regression analysis, and response optimization techniques detailed in the following sections.

The main effects plot for ***S***/***N*** ratios (Fig. 5) graphically summarizes the influence of each control factor – tungsten volume fraction, temperature, and load – on the *W–Cu* composites' wear performance according to the "smaller-the-better" criterion. The plot reveals the relative significance of each parameter and aids in identifying the optimal level for minimizing the wear rate.

According to the main effects plot for ***S***/***N*** ratios (Fig. 5), temperature is the most influential factor for minimizing wear (lower-the-better). The ***S***/***N*** ratio exhibits a substantial increase from –12.5 dB at 160 °C to –11.2 dB at 200 °C, corresponding to improved wear resistance at higher temperatures. The effect of tungsten volume fraction is non-linear, with an optimum at 30% (–11.6 dB), beyond which it decreases at 40%. This suggests an optimal balance between reinforcement content and matrix integrity. Load shows a weaker but positive correlation with the ***S***/***N*** ratio, increasing from –12.0 dB at 80 N to –11.6 dB at 100 N. Therefore, the optimal conditions for minimizing wear are identified as 30 vol.% tungsten, 200 °C, and 100 N, with temperature exerting the dominant effect.

ANOVA was conducted to assess the statistical significance and quantify the relative contribution (%) of tungsten volume fraction, temperature, and load to the wear rate variance. The *ANOVA* results are presented in Table 6.

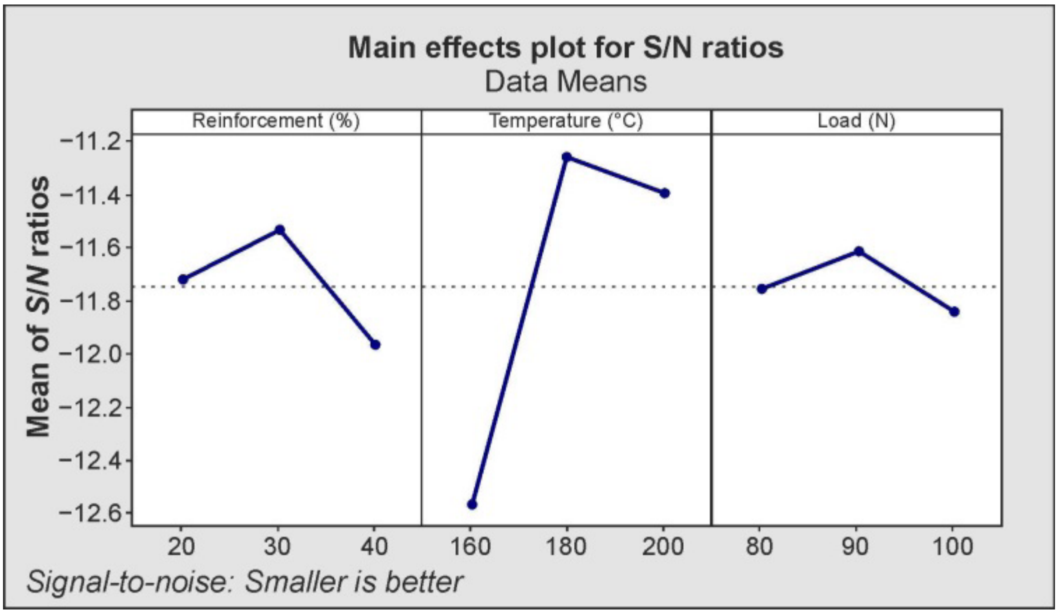

Fig. 5. Main effects plot for *S*/*N* ratios

Table 6

Analysis of variance

Source	*DF*	Seq *SS*	Adj *SS*	Adj *MS*	***F***-value	***P***-value
Reinforcement (%)	2	0.053408	0.053408	0.026704	144.87	0.007
Temperature (°C)	2	0.642781	0.642781	0.321390	1743.53	0.001
Load (N)	2	0.012713	0.012713	0.006356	34.48	0.028
Residual error	2	0.000369	0.000369	0.000184		
TOTAL	8	0.709271				

The *ANOVA* analysis quantifies the influence of each control variable on the wear rate of the *W–Cu* composites. Temperature is identified as the most significant factor, accounting for approximately 90.6% of the total variance, with a very high ***F***-value of 1,743.53 and a ***p***-value < 0.001, indicating extreme statistical significance. Tungsten volume fraction also has a significant effect, contributing about 7.5% of the variance (***F***-value = 144.87, ***p***-value = 0.007). Load has a relatively small but statistically significant impact, accounting for only ~1.8% of the variance (***F***-value = 34.48, ***p***-value = 0.028). Furthermore, the model residuals constitute less than 0.05% of the total variance, confirming an excellent model fit and supporting the reliability of the experimental data.

These quantitative results corroborate the trends observed in the main effects plot and provide robust evidence that temperature is the primary parameter to control for optimizing the wear performance of *W–Cu* composites. The model regression coefficients are reported in Table 7.

Table 7

Model Summary Interpretation

Standard Error of the Estimate (S)	Coefficient of determination (R^2)	Adjusted coefficient of determination (R^2adj)
0.0136	99.95%	99.79%

The regression model demonstrates excellent predictive capability and a strong fit to the experimental data for the wear rate of *W–Cu* composites. The standard error of the estimate (***S***) is 0.0136, indicating very little scatter in the predicted values. The coefficient of determination (R^2) is 99.95%, meaning that 99.95% of the variance in the wear rate is explained by the model. The adjusted R^2 value (99.79%), which accounts for the number of predictors, is also exceptionally high, confirming that the model is not overfitted and should generalize well. Therefore, the model incorporating the three control factors (tungsten volume fraction, temperature, and load) provides a robust and accurate representation of the wear behavior.

A linear regression model was developed to predict the wear rate as a function of the three parameters. The resulting regression equation is:

$$\text{Wear rate} = 5.96 + 0.00540 \times W\,(\text{vol.\%}) - 0.01336 \times \boldsymbol{T}\,(^\circ\text{C}) + 0.00178 \times \boldsymbol{L}\,(\text{N}).$$

Analysis of the regression coefficients reveals that the wear rate increases slightly with tungsten volume fraction (coefficient = +0.00540), although this effect is modest compared to that of temperature. The wear rate decreases significantly with increasing temperature (coefficient = –0.01336), underscoring its dominant role in enhancing wear resistance. A marginal increase in wear rate with load (coefficient = +0.00178) is also observed, which aligns with the *ANOVA* and main effects plot results.

To validate the model, the predicted wear rates were compared with the experimental values for all nine *Taguchi* trials, as summarized in Table 8.

Table 8

Comparison of experimental and predicted wear rates with percentage error

Wear rate (experimental) ($mm^3/(N·m)$)	Wear rate (theoretical) ($mm^3/(N·m)$)	Error (%)
4.245	4.073	4.229
3.593	3.823	6.014
3.759	3.574	5.178
3.583	3.860	7.180
3.575	3.610	0.969
4.199	4.162	0.890
3.817	3.647	4.663
4.310	4.199	2.643
3.794	3.949	3.926

Fig. 6 presents the comparison between experimental and predicted wear rates. The prediction errors range from 0.89% to 7.18%, with a mean error of 4.28%. Prediction errors below 10% are generally considered acceptable for engineering models. The individual and overall error rates are sufficiently low to confirm the model's validity and its reliability for predicting wear rates within the studied parameter range.

Thus, the model's validation – supported by the very high R^2 value (99.95%) and the low standard error (***S*** = 0.0136) – demonstrates its robustness and utility for optimizing *W–Cu* composite materials in applications where wear resistance is a critical performance criterion.

The objective of this experimental validation was to confirm the optimal parameters identified through the regression model and *Taguchi DOE*: tungsten volume fraction of 30%, temperature of 200 °C, and load of 80 N. These parameters were selected as they yielded the lowest predicted wear rate and were consistent with the trends from the main effects plot and *ANOVA*.

A verification experiment was conducted using this optimal parameter set. The experimentally measured wear rate was then compared to the value predicted by the regression model to assess the model's accuracy.

The results confirm the *Taguchi* method's prediction that the optimal combination – 30 vol.% tungsten, 180 °C, and 90 N – would yield the lowest wear rate and greatest wear stability. The experimental wear rate measured under these conditions was 4.719×10^{-7} $mm^3/(N·m)$, while the regression model predicted a value of 5.240×10^{-7} $mm^3/(N·m)$, resulting in a relative error of 9.24% (Table 9).

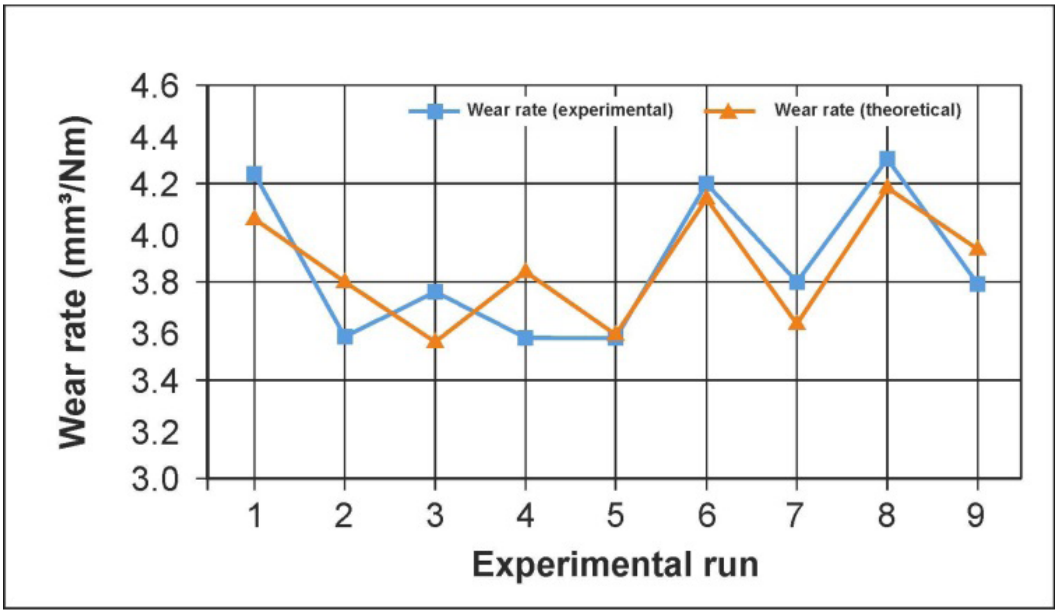

Fig. 6. Comparison of experimental and predicted wear rates

Table 9

Confirmation Test

Optimization method	Optimum Parameter	Wear rate, $\times 10^{-7}$ mm³/(N·m)		Error(%)
		Experimental	Predicted	
Taguchi	Reinforcement: 30%, Temperature: 200 °C, Load: 80 N	4.719	5.240	9.24

This error is considered acceptable in tribological studies, given the inherent complexity of factors such as environmental fluctuations, the dynamic nature of surface oxide layers, and material microstructural heterogeneity, which are challenging to quantify precisely. While the Taguchi approach provides a reliable and robust identification of the optimum, its predictive accuracy is typically lower than that of regression-based or response surface methodology (*RSM*) models, which often achieve prediction errors below 5%.

Conclusions

This study developed a statistically robust methodology for minimizing the dry-sliding wear rate of *W–Cu* composites, combining *OVAT* screening of key parameters with a *Taguchi* L_9 orthogonal array. The *OVAT* trials revealed that wear rate increases significantly above an 80 N load, while elevated temperature (160–200 °C) promotes the formation of a protective oxide glaze, thereby reducing material loss.

The *Taguchi DOE* established temperature as the dominant factor, accounting for 90.6% of the variance ($\boldsymbol{F} = 1743$, $\boldsymbol{p} < 0.001$), followed by tungsten volume fraction (7.5%) and applied load (1.8%). Regression analysis of the *DOE* data produced a linear model with $\boldsymbol{R^2} = 99.95\%$ and a mean absolute prediction error of 4.0% for predicting wear rate as a function of the three variables.

The identified robust optimum condition – 30 vol.% *W*, 180 °C, and 80 N – yielded an experimental wear rate of 3.498×10^{-7} mm³/(N·m). This value differed by only 4.6% from the model prediction and represented a 21% improvement in wear resistance compared to the worst-case condition in the experimental design.

These findings provide materials and design engineers with a practical parameter envelope that optimizes both wear resistance and robustness against process variations. The proposed methodology is directly applicable to optimizing components such as resistance welding electrodes, heavy-duty circuit breaker contacts, and other high-temperature electrical contacts.

Future work should expand the design space to include additional factors such as sliding velocity and humidity, explore second-order interactions via larger orthogonal arrays or hybrid response surface methodology (*RSM*)-*Taguchi* approaches, and investigate correlations between the macroscopically optimized conditions and the microstructural characteristics of tribo-oxides and the tungsten particle network.

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Conflicts of Interest

The authors declare no conflict of interest.