

Wear of copper-based hybrid composites reinforced with graphite and recycled porcelain particles

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Abstract

The development of copper-based hybrid composites with enhanced wear resistance remains essential to extend their applications in demanding tribological environments. In the present study, recycled electrical porcelain waste was incorporated as a ceramic reinforcement into Cu-graphite hybrid composites fabricated by powder metallurgy. A Taguchi design was employed to investigate the effects of graphite and porcelain contents, applied load and sliding time on the composite properties and wear behaviour. Sixteen compositions were prepared with 0–6 vol. % graphite and 0–9 vol. % porcelain, while wear tests were conducted under loads of 10–25 N and sliding times of 10–25 min. Increasing reinforcement content reduced density and increased porosity from 2.05 to 9.86 %, whereas adding porcelain increased hardness to 56.8 HV. Taguchi analysis identified porcelain content as the most influential factor affecting wear. The hybrid reinforcement improved wear resistance through ceramic strengthening and the formation of a protective graphite-rich tribolayer, resulting in an approximately 63.5 % reduction in mass loss compared with pure copper. A confirmation experiment under the optimum conditions yielded a prediction error of only 4.9 %, demonstrating good agreement between the predicted and experimental results and confirming the effectiveness and predictive capability of the Taguchi optimisation approach.

1. Introduction

Copper-graphite composites have attracted significant interest for tribological applications owing to the combination of copper's excellent thermal and electrical conductivity and graphite's self-lubricating properties. The formation of a graphite transfer film during sliding reduces friction and wear, enhancing the tribological performance of the composites. Consequently, these materials are widely used in electrical contacts, bearings and other engineering applications requiring high reliability and low maintenance [1-3].

Powder metallurgy is an effective route for manufacturing copper-based composites due to

its ability to ensure precise compositional control and uniform reinforcement distribution. Copper composites reinforced with ceramic particles produced by powder metallurgy exhibit enhanced hardness, strength and wear resistance, as the hard reinforcements improve load-bearing capacity and suppress plastic deformation under sliding conditions. Therefore, the combination of graphite lubrication and ceramic strengthening offers a promising approach to developing high-performance, multifunctional copper composites [3,4].

The use of industrial and ceramic wastes as reinforcements in metal matrix composites has attracted growing interest due to their environmental and economic benefits. Among these materials, porcelain waste powder, rich in silica and alumina phases, offers high hardness and the potential to enhance wear resistance. Previous



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studies have shown that ceramic reinforcements improve surface hardness, reduce wear and promote the formation of protective tribolayers under sliding conditions [5-7].

To further improve the wear resistance of copper-graphite systems, several studies focused on incorporating hard ceramic reinforcements into the copper matrix. Şap et al. [3] fabricated Cu-5Gr hybrid composites reinforced with Al_2O_3 and Cr_3C_2 particles using powder metallurgy and hot-pressing techniques. Their findings indicated that increasing the ceramic reinforcement content enhanced hardness and bending strength while significantly reducing wear. Similarly, Ankit et al. [8] investigated Cu-graphite composites reinforced with nano-TiC particles and reported substantial improvements in wear resistance owing to the combined effect of graphite lubrication and ceramic particle strengthening.

Sulima et al. [9] examined the effect of zirconium diboride (ZrB_2) additions on the physical, mechanical and tribological properties of copper matrix composites fabricated by powder metallurgy and spark plasma sintering. Their results revealed that increasing the ZrB_2 content significantly enhanced hardness, compressive strength and wear resistance owing to the high hardness and load-bearing capability of the ceramic particles. The study further showed that the improved wear behaviour was closely associated with the effective restriction of plastic deformation and material removal during sliding.

Zaki et al. [10] investigated Cu-based nanocomposites reinforced with hybrid ceramic particles and reported significant improvements in hardness, wear resistance and dimensional stability compared with unreinforced copper. The enhanced wear behaviour was attributed to the high load-bearing capacity of the ceramic phases, which effectively restricted plastic deformation and minimised material removal during sliding. Similarly, Xu et al. [11] developed Cu matrix composites reinforced with Mo_2BC ceramic particles and demonstrated remarkable improvements in both mechanical and tribological properties. Their results revealed that the ceramic reinforcement suppressed adhesive wear, promoted grain refinement and facilitated the formation of protective tribo-oxide layers, thereby reducing friction and wear.

Zhang et al. [12] demonstrated that zirconia-toughened alumina reinforcement significantly improved the mechanical and tribological

properties of copper matrix composites by enhancing load-bearing capacity, strengthening interfacial bonding and promoting the formation of protective tribolayers that reduced wear during sliding.

Although recent studies have demonstrated the effectiveness of ceramic reinforcements in Cu-graphite composites [3,8-12], they have mainly focused on conventional ceramic phases such as Al_2O_3 , TiC, ZrB_2 and Mo_2BC . The use of recycled electrical porcelain in Cu-graphite composites, particularly with systematic optimisation of both material composition and sliding conditions, remains insufficiently investigated. Therefore, the present study combines recycled porcelain reinforcement with a Taguchi-based design to simultaneously evaluate and optimise the porcelain and graphite contents, applied load and sliding time. The Taguchi approach further identifies the relative influence of these parameters through the S/N ratio and response ranking, providing an efficient basis for minimising wear and determining the optimum conditions.

2. Materials and experimental procedure

The raw materials employed in the study included dendritic copper powder ($\leq 45 \mu\text{m}$, 99.5 % purity), flake graphite powder ($\leq 63 \mu\text{m}$, 99.8 % purity) and recycled porcelain powder ($\leq 53 \mu\text{m}$) obtained from discarded electrical insulators. The corresponding densities of copper, graphite and porcelain were 8.94, 2.26 and 2.30 g/cm^3 , respectively. Recycled porcelain powder was prepared from discarded electrical insulators through crushing, milling and particle-size classification. The porcelain pieces were initially crushed and subsequently ground using a Retsch RM 200 mortar grinder for 15 min. The ground material was then subjected to particle-size classification using a CONTROLS D403 automatic sieve shaker to obtain the required particle size ($\leq 53 \mu\text{m}$). The chemical composition of the porcelain powder was determined by X-ray fluorescence (XRF) analysis, and the obtained results are presented in Table 1.

Table 1. XRF composition of recycled porcelain

Oxide	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	MgO	Other
wt. %	62.87	28.14	0.86	0.48	0.73	6.92

Thereafter, copper-based hybrid composites were fabricated using the powder metallurgy

route. A total of sixteen compositions were produced by varying the graphite and porcelain contents from 0–6 vol. % and 0–9 vol. %, respectively, while copper constituted the balance of each formulation. Prior to compaction, the powders were mechanically mixed for 30 min to ensure homogeneous distribution of the reinforcement phases within the copper matrix. The blended powder mixtures were uniaxially compacted at 500 MPa using a Hoytom universal testing machine and held under pressure for 1 min to produce cylindrical green compacts with a diameter of 10 mm and a height of 6 mm. The compacts were subsequently sintered at 900 °C for 2 h in an argon protective atmosphere to minimise oxidation. The heating rate was maintained at 4 °C/min until the sintering temperature was reached. After the 2 h holding period, the furnace was switched off and the samples were allowed to cool gradually inside the furnace to room temperature.

3. Characterisation

The experimental density and porosity of the fabricated composites were determined using Archimedes' principle in accordance with ASTM B962. The theoretical density was calculated using the rule of mixtures based on the densities of copper, graphite and porcelain previously mentioned. The experimental density, theoretical density and porosity were evaluated using Equations (1), (2) and (3) [13,14].

$$ED = \frac{M_d}{(M_d - M_i)} D_w, \quad (1)$$

where ED is experimental density, M_d is the mass of the dry specimen, M_i is the mass of the specimen when suspended in distilled water and D_w is the density of water; water density was used to convert the displaced water mass to the specimen volume, which is required to determine the experimental density.

$$TD = \sum TD_i X_i, \quad (2)$$

where TD is the theoretical density, TD_i is the theoretical density of the individual composite elements and X_i is the volume fraction of the individual elements present in the composite.

$$P = \left(1 - \frac{ED}{TD} \right) 100, \quad (3)$$

where P is the porosity.

The microhardness of the composites was measured using a Metkon THV-501E Vickers microhardness tester in accordance with ASTM E384. A 500 g load was applied for a dwell time of 20 s. Five indentations were made on each specimen at representative locations covering both the matrix and reinforcement phases, and the average value was reported.

Dry sliding wear tests were conducted using a Ducom ED-201 pin-on-disc tribometer in accordance with ASTM G99. The counter-body was a hardened steel disc with a hardness of 62 HRC. During testing, the disc rotated against a stationary specimen along a wear track diameter of 60 mm at a rotational speed of 480 rpm, corresponding to a sliding speed of 1.51 m/s. Wear experiments were conducted under applied loads of 10 N (0.127 MPa), 15 N (0.191 MPa), 20 N (0.255 MPa) and 25 N (0.318 MPa) and sliding durations of 10, 15, 20 and 25 min. The specimens were weighed before and after each test using an electronic balance with a readability of 0.0001 g to determine the amount of mass loss. Prior to testing, both the specimen and the steel disc were cleaned with acetone to remove contaminants and ensure consistent test conditions. Three specimens were tested for each experimental condition, and the reported results represent the average values obtained from these measurements. Furthermore, the results from the sixteen experiments designed according to the Taguchi L16 orthogonal array (Table 2) were analysed using the Taguchi method to evaluate the influence of the selected parameters and identify the optimal parameters.

Table 2. Factors and their levels used in the Taguchi L16 experimental design

Factor	Level			
	1	2	3	4
Graphite, vol. %	0	2	4	6
Porcelain, vol. %	0	3	6	9
Applied load, N	10	15	20	25
Sliding time, min	10	15	20	25

Following the wear tests, the worn surfaces of the specimens were examined using a Tescan Vega 3 scanning electron microscope (SEM). Energy-dispersive X-ray spectroscopy (EDS) was performed to analyse the elemental composition of the wear tracks and support the interpretation of the wear mechanisms.

4. Results and discussion

4.1 Density and porosity

The theoretical and experimental density values, presented in Table 3, exhibited a gradual decline as graphite and porcelain contents increased. This reduction is primarily attributed to the lower densities of graphite and porcelain compared with the copper matrix. Accordingly, the partial substitution of copper by these reinforcement phases decreased the overall composite density in agreement with the rule of mixtures.

Furthermore, the incorporation of graphite and porcelain particles led to a noticeable increase in porosity. The porosity increased from 2.05 % in the unreinforced copper sample to 9.86 % in the composite with the highest reinforcement fraction. This trend can be attributed to the reduced compressibility of the powder mixtures and the inhibition of densification during sintering. Graphite particles exhibit poor wettability with copper and tend to weaken interparticle bonding, whereas porcelain particles, owing to their rigid ceramic nature, impede particle rearrangement and limit diffusion-controlled mass transport during sintering. Consequently, the presence of these reinforcement phases restricts densification and

promotes the formation of residual pores within the composite structure. The progressive increase in porosity with increasing reinforcement content suggests that the addition of graphite and porcelain reduced the packing efficiency of the powder mixture and limited the extent of densification during sintering. This interpretation is consistent with the simultaneous decrease in measured density and increase in porosity, although direct morphological evidence of pores was not obtained in the present study. The noticed decrease in density and corresponding increase in porosity are consistent with findings reported for Cu-graphite and ceramic-reinforced copper composites fabricated by powder metallurgy [7,15,16].

Previous studies have demonstrated that increasing the volume fraction of reinforcement particles hinders particle packing efficiency and sintering kinetics, resulting in lower densification and higher residual porosity. Controlled residual porosity may also provide localised sites for retaining graphite debris, potentially supporting the formation and stability of a lubricating tribolayer. This interpretation is consistent with previous findings for porous Fe-Cu bearing materials, where residual pores can act as lubricant reservoirs and contribute to self-lubricating behaviour [17].

Table 3. Density, porosity and hardness results

Copper, vol. %	Graphite, vol. %	Porcelain, vol. %	Theoretical density, g/cm ³	Experimental density, g/cm ³	Porosity, %	Hardness HV
100	0	0	8.960	8.777 ± 0.115	2.05	47.32 ± 0.71
98	2	0	8.824	8.546 ± 0.489	3.16	46.57 ± 0.71
96	4	0	8.689	8.354 ± 0.520	3.86	45.73 ± 0.58
94	6	0	8.554	8.213 ± 0.261	3.99	48.00 ± 0.24
97	0	3	8.760	8.405 ± 0.389	4.06	52.97 ± 1.42
95	2	3	8.625	8.271 ± 0.347	4.10	49.92 ± 0.80
93	4	3	8.489	8.113 ± 0.090	4.43	48.52 ± 0.72
91	6	3	8.354	7.892 ± 0.114	5.54	52.73 ± 0.90
94	0	6	8.560	8.184 ± 0.194	4.39	53.60 ± 1.24
92	2	6	8.425	8.081 ± 0.024	4.09	52.86 ± 0.23
90	4	6	8.290	7.894 ± 0.024	4.77	50.20 ± 0.91
88	6	6	8.154	7.686 ± 0.313	5.74	49.95 ± 1.26
91	0	9	8.360	7.853 ± 0.788	6.07	56.80 ± 0.84
89	2	9	8.225	7.587 ± 0.488	7.76	54.99 ± 1.22
87	4	9	8.090	7.384 ± 0.541	8.73	54.23 ± 1.05
85	6	9	7.955	7.171 ± 0.194	9.86	52.70 ± 0.64

4.2 Hardness

As shown in Table 3, the hardness values were strongly affected by the type and content of the reinforcement phases. The addition of graphite alone resulted in a slight decrease in hardness due to its soft, solid-lubricating nature and limited load-bearing capacity, thereby reducing the copper matrix's overall resistance to plastic deformation. Similar behaviour has been reported for Cu-graphite composites produced by powder metallurgy [18].

In contrast, incorporating porcelain particles significantly improved hardness, reaching a maximum of 56.80 HV at 9 vol. % porcelain. This enhancement is attributed to the high hardness of the ceramic phase, which strengthens the copper matrix by impeding dislocation movement and increasing resistance to localised plastic deformation. In addition, the porcelain particles facilitate load transfer from the matrix to the harder reinforcement phase, thereby improving the overall hardness [19,20].

For the hybrid composites, the hardness values remained higher than those of pure copper but lower than those of porcelain-reinforced composites without graphite. This behaviour results from the competing effects of the hard ceramic particles, which promote strengthening, and the soft graphite phase, which tends to reduce hardness. Furthermore, the increased porosity at

higher reinforcement contents may partially offset the strengthening effect of the ceramic particles. Similar trends have been reported in hybrid copper matrix composites reinforced with ceramic and carbon-based phases [21,22].

4.3 Wear and wear mechanism

The experimental results obtained from the 16 Taguchi trials, including the mass loss and corresponding signal-to-noise (S/N) ratios, are presented in Table 4. The S/N ratios were calculated using the smaller-is-better criterion, where a higher S/N ratio indicates lower wear. The results in Table 4 show that the wear varied considerably with changes in the reinforcement contents and testing conditions, indicating the significant effects of the selected control factors on the wear behaviour of the developed Cu-graphite porcelain composites.

To further quantify the wear behaviour of the developed composites, the specific wear rate was calculated for all 16 Taguchi trials based on the measured mass loss, sample density, applied load and sliding distance. The calculated specific wear rate values are presented in Table 5. The specific wear rate provides a normalised measure of material mass loss with respect to the applied load and sliding distance, enabling a more direct comparison of wear behaviour across different experimental conditions.

Table 4. Taguchi L16 wear response of Cu-graphite porcelain composites

Graphite, vol. %	Porcelain, vol. %	Applied load, N	Sliding time, min	Mass loss, g	S/N ratio, dB
0	0	10	10	0.0096	40.35
2	0	15	15	0.0129	37.79
4	0	20	20	0.0155	36.19
6	0	25	25	0.0165	35.65
0	3	15	20	0.0128	37.85
2	3	10	25	0.0135	37.39
4	3	25	10	0.0122	38.27
6	3	20	15	0.0108	39.33
0	6	20	25	0.0108	39.33
2	6	25	20	0.0096	40.35
4	6	10	15	0.0078	42.15
6	6	15	10	0.0068	43.34
0	9	25	15	0.0075	42.49
2	9	20	10	0.0058	44.73
4	9	15	25	0.0045	46.93
6	9	10	20	0.0035	49.11

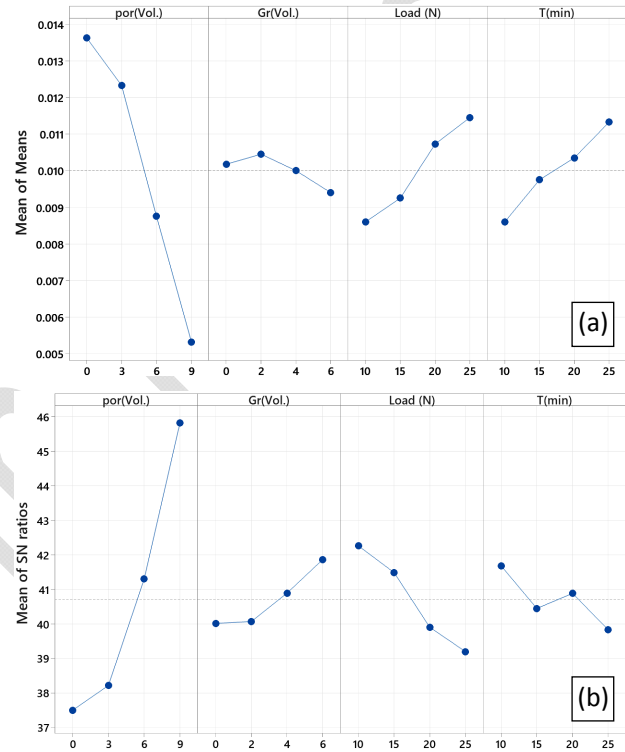
Table 5. Specific wear rate of the composites

Graphite, vol. %	Porcelain, vol. %	Specific wear rate, mm ³ /Nm
0	0	1.207×10^{-4}
2	0	7.405×10^{-5}
4	0	5.120×10^{-5}
6	0	3.548×10^{-5}
0	3	5.603×10^{-5}
2	3	7.206×10^{-5}
4	3	6.639×10^{-5}
6	3	5.035×10^{-5}
0	6	2.913×10^{-5}
2	6	2.622×10^{-5}
4	6	7.271×10^{-5}
6	6	6.510×10^{-5}
0	9	2.811×10^{-5}
2	9	4.219×10^{-5}
4	9	1.794×10^{-5}
6	9	2.694×10^{-5}

The specific wear rate tended to decrease as porcelain content increased, indicating improved wear resistance of the composites. The lowest value was obtained for the composite containing 4 vol. % graphite and 9 vol. % porcelain, whereas the highest value was noticed for pure copper. This trend further confirms the beneficial effect of porcelain reinforcement in reducing material mass loss under sliding conditions.

To quantitatively evaluate the relative influence of these control factors on wear behaviour, an analysis of variance (ANOVA) was subsequently performed. The ANOVA results are presented in Table 6. Porcelain content was identified as the most influential factor governing wear, with a contribution ratio of 77.68 %, followed by applied load at 10.73 %. In contrast, graphite content and

sliding time showed considerably lower contributions of 4.09 and 3.27 %, respectively. Consistent with the response tables (Tables 7 and 8) and the main effects plot (Fig. 1), porcelain also exhibited the highest Delta value and ranked first among the investigated parameters, indicating that increasing the porcelain content progressively increased the S/N ratio. The higher S/N ratio reflects lower wear and a more stable response, confirming the effectiveness of porcelain reinforcement in improving wear resistance.

**Figure 1.** Main effects plot for mass loss: (a) means and (b) S/N ratios (smaller-is-better)

The adequacy of the developed model for the wear response was further evaluated using the coefficient of determination (R^2). The obtained R^2 value was 0.9100, indicating that approximately 91.0 % of the variation in mass loss was explained

Table 6. Analysis of variance for SN ratios

Source	Degrees of freedom	Sequential sum of squares	Adjusted sums of squares	Adjusted mean squares	F-value	p-value	Contribution, %
Porcelain, vol. %	3	172.117	172.117	57.372	18.37	0.020	77.68
Graphite, vol. %	3	9.057	9.057	3.019	0.97	0.511	4.09
Applied load, N	3	23.784	23.784	7.928	2.54	0.232	10.73
Sliding time, min	3	7.254	7.254	2.418	0.77	0.581	3.27
Residual error	3	9.367	9.367	3.122			4.23
Total	15	221.579					100

by the investigated control factors, namely porcelain content, graphite content, applied load and sliding time. The corresponding adjusted R^2 was 0.8773, indicating that the model retained a high explanatory capability after accounting for the number of predictors. These results further support the reliability of the statistical analysis for describing the variation in wear under the investigated conditions.

Table 7. Response table for S/N ratios (smaller-is-better)

Level	Porcelain, vol. %	Graphite, vol. %	Applied load, N	Sliding time, min
1	37.50	40.01	42.26	41.68
2	38.21	40.07	41.48	40.44
3	41.30	40.89	39.90	40.88
4	45.82	41.86	39.19	39.83
Delta	8.32	1.85	3.06	1.85
Rank	1	3	2	4

Table 8. Response table for means

Level	Porcelain, vol. %	Graphite, vol. %	Applied load, N	Sliding time, min
1	0.013625	0.010175	0.008600	0.008600
2	0.012325	0.010450	0.009250	0.009750
3	0.008750	0.010000	0.010725	0.010350
4	0.005325	0.009400	0.011450	0.011325
Delta	0.008300	0.001050	0.002850	0.002725
Rank	1	4	2	3

These statistical findings are further supported by the SEM analysis (Fig. 2). All micrographs in Figure 2 were obtained from the same Cu / 6 vol. % graphite / 9 vol. % porcelain composite sample, but at different magnifications. The worn surface exhibits relatively shallow grooves, limited plastic deformation and localised material removal, indicating the beneficial role of the hard porcelain particles in supporting the applied load, reducing penetration of the steel counter-body and suppressing plastic deformation during sliding. These features contribute to the improved wear resistance of the hybrid composite. Similar results have been reported for ceramic-reinforced copper matrix composites, where hard ceramic phases enhance wear resistance by increasing surface hardness and reducing plastic deformation during sliding [7,23].

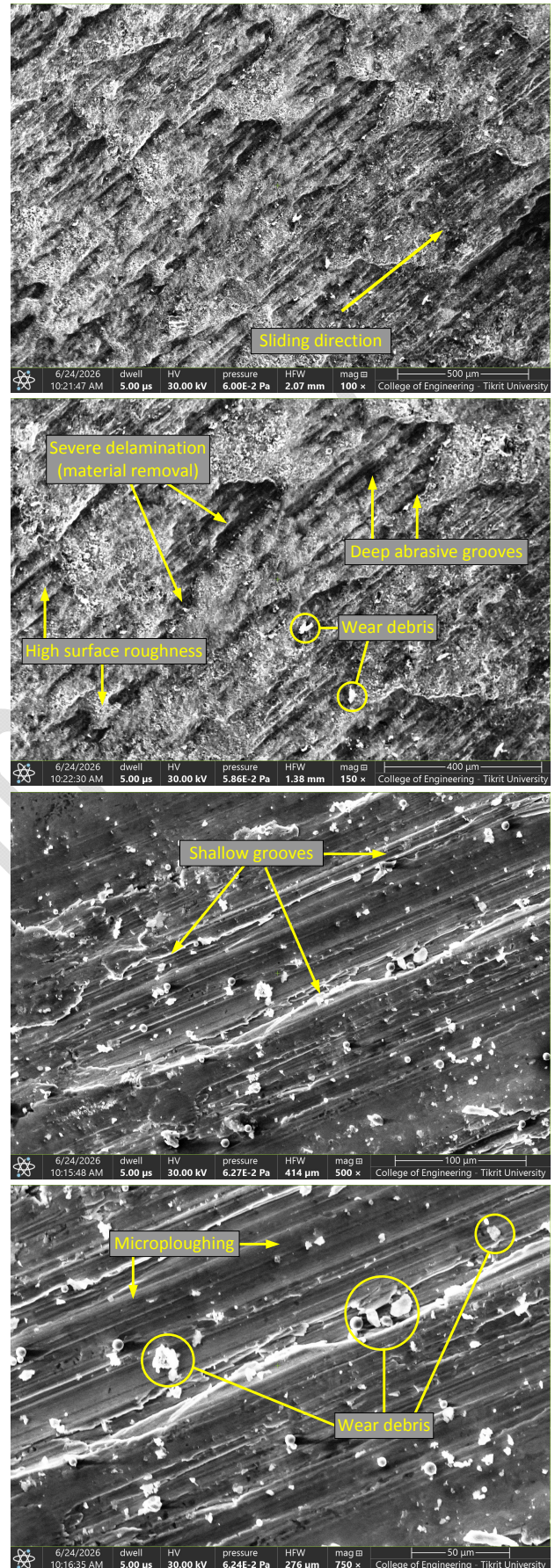


Figure 2. SEM images of Cu / 6 vol. % graphite / 9 vol. % porcelain composite (tested at 10 N applied load and for 10 min sliding time) at different magnifications

The Taguchi analysis further revealed that the combined addition of porcelain and graphite produced the highest S/N ratio and the lowest wear, as summarised in Table 4. The optimum composite, containing 6 vol. % graphite and 9 vol. % porcelain, achieved a maximum S/N ratio of 49.11 dB and a minimum mass loss of 0.0035 g, confirming the superior wear behaviour of the hybrid reinforcement system. This improvement is attributed to the synergistic effect of ceramic strengthening and solid lubrication. During sliding, the hard porcelain particles act as load-bearing sites and restrict plastic deformation of the copper matrix, while graphite helps reduce direct metal-to-metal contact through a lubricating transfer layer. This combined effect limits microploughing and material removal, consistent with the shallower grooves and reduced surface damage noticed by SEM. At higher loads, increased contact stress can disrupt this protective effect, promoting asperity penetration and plastic deformation, thereby increasing wear.

The SEM image in Figure 3 represents the analysed area over which the EDS elemental mapping was obtained. The EDS analysis of the Cu / 6 vol. % graphite / 9 vol. % porcelain composite presented in Figure 4 was performed on the worn surface region

shown in Figure 3. The EDS results support the presence of Si, Al and Ca, which are associated with the recycled porcelain reinforcement, while the Fe signal indicates material transferred from the steel counter-body. This indicates that these ceramic phases remained embedded within the wear track and contributed to load support by restricting plastic deformation and material removal during sliding. Similar mechanisms have been widely reported for copper-graphite composites reinforced with ceramic particles [24,25].

The influence of the applied load was also evident from the Taguchi response analysis. As the applied load increased, the corresponding S/N ratio decreased, indicating increased wear under higher contact stresses. This behaviour is attributed to deeper asperity penetration, which intensifies plastic deformation, abrasive interaction and frictional heating, thereby accelerating material removal. Despite this trend, the hybrid composite consistently exhibited better wear resistance than pure copper owing to the load-bearing effect of the porcelain particles and the lubricating action of graphite. Comparable trends have also been reported for ceramic-reinforced copper matrix composites subjected to increasing applied loads [2,26].

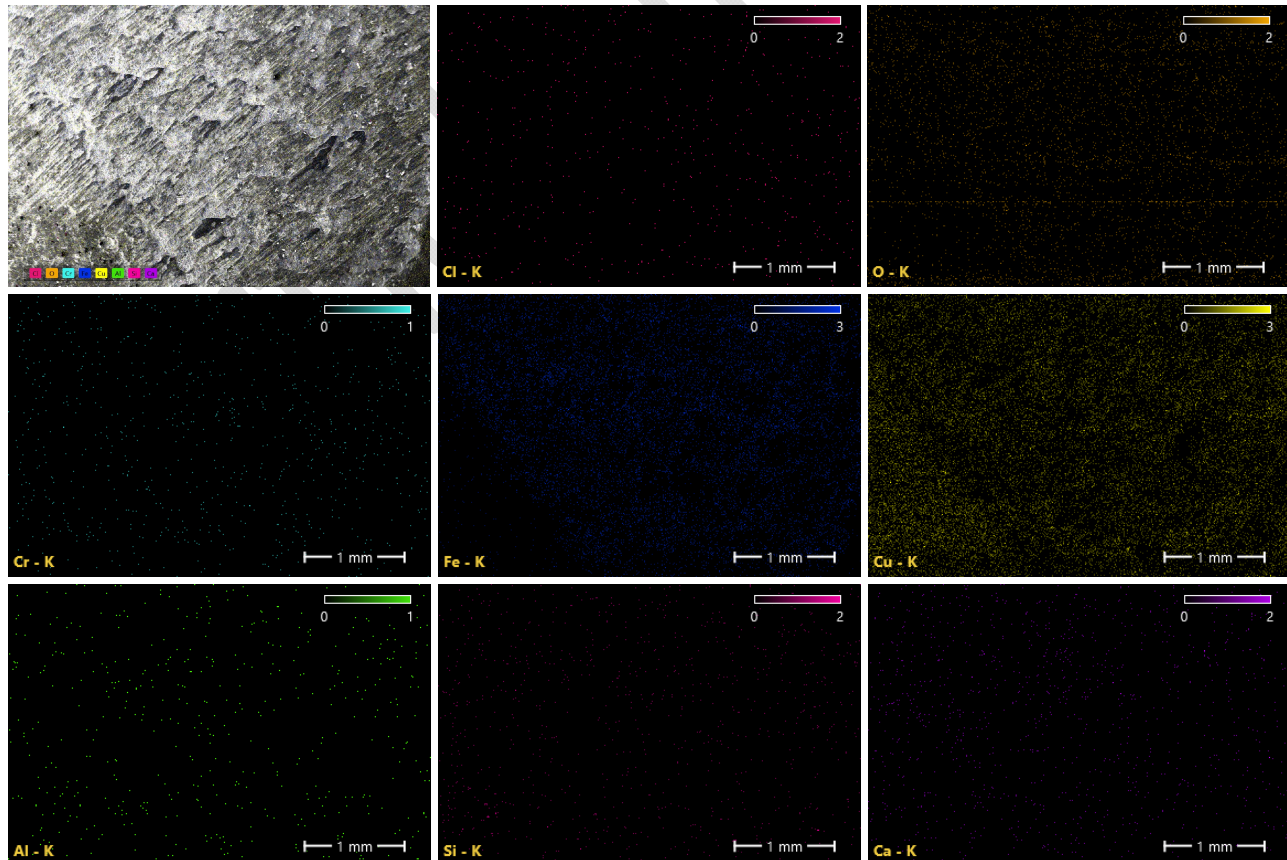
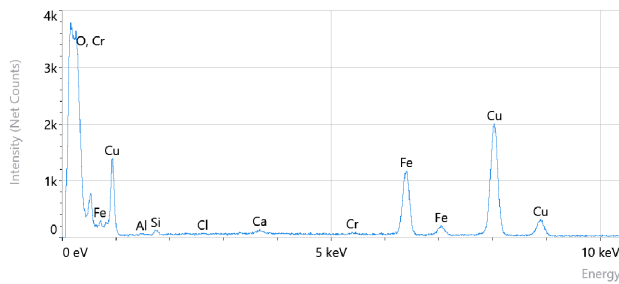


Figure 3. EDS elemental mapping of the worn surface of Cu / 6 vol. % graphite / 9 vol. % porcelain composite (tested at 10 N applied load and for 10 min sliding time)



Element	O	Al	Si	Cl	Ca	Cr	Fe	Cu
wt. %	0.9	0.6	1.9	0.2	0.7	0.4	23.2	72.1

Figure 4. EDS analysis of the worn surface of Cu / 6 vol. % graphite / 9 vol. % porcelain composite (tested at 10 N applied load and for 10 min sliding time)

A similar trend was noticed for sliding time. Increasing the sliding duration gradually decreased the S/N ratio because of progressive material removal during repeated sliding cycles. However, its relatively small Delta value indicates that sliding time had a much smaller influence on wear than porcelain content and applied load, confirming that the composite composition was the primary factor governing wear behaviour under the investigated conditions. Overall, the Taguchi analysis demonstrated that porcelain content was the dominant parameter controlling wear behaviour and that the hybrid reinforcement of porcelain and graphite provided the optimum properties among the investigated composites.

4.4 Confirmation experiment

To validate the optimisation results obtained from the Taguchi analysis, a confirmation experiment was conducted using the optimum parameter combination identified by the Taguchi response optimizer, as shown in Figure 1 (9 vol. % porcelain, 6 vol. % graphite, applied load of 10 N and sliding time of 10 min). To assess the repeatability of the optimised condition, three independent specimens were tested under the same conditions and the experimental mass loss was calculated as the average of the three measurements. The Taguchi response optimizer predicted a mass loss of 0.0019062 g with a corresponding predicted S/N ratio of 49.4948 dB. The experimentally measured average mass loss was 0.0020 g, obtained using an analytical balance with a readability of 0.0001 g. The difference between the predicted and experimental values was 4.9 %, indicating good agreement. The close agreement and consistent measurements among the three specimens provide evidence of the repeatability of the

optimised condition and support the reliability of the Taguchi-based optimisation approach.

5. Conclusion

The present study investigated the effects of the addition of recycled porcelain and graphite on the physical, mechanical and wear properties of Cu-based hybrid composites fabricated by powder metallurgy. Based on the obtained results, the following conclusions can be drawn.

The incorporation of graphite and porcelain reduced the densification efficiency during sintering, resulting in an increase in porosity from 2.05 % for pure copper to 9.86 % for the highly reinforced composite.

Porcelain particles effectively enhanced the hardness of the copper matrix. The maximum hardness reached 56.80 HV, representing an improvement of approximately 20 % compared with unreinforced copper.

Taguchi and ANOVA analyses identified porcelain content as the most influential parameter affecting wear, indicating that ceramic reinforcement played the dominant role in controlling material loss during sliding.

The combined addition of porcelain and graphite significantly enhanced the wear behaviour of the composites through the synergistic effects of ceramic strengthening and solid lubrication. The optimum composite exhibited a 63.5 % reduction in wear compared with pure copper, demonstrating the effectiveness of the hybrid reinforcement strategy.

Although increasing the applied load and sliding time promoted wear, the reinforced composites maintained superior wear resistance owing to the load-bearing capability of porcelain particles and the lubricating action of graphite.

Overall, the present findings demonstrate that recycled electrical porcelain waste is a promising ceramic reinforcement for developing cost-effective copper-based tribological composites, offering a viable approach for enhancing wear resistance while promoting the beneficial utilisation of industrial ceramic waste.

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