High anti-arc erosion performance of the Al$_2$O$_3$ reinforced Cu@W composites for high voltage circuit-breaker contacts

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1. Introduction

The ultrahigh voltage transmission is an efficient strategic project for long-distance power transmission. The power transmission distances are typically ranged between 400 to 1000 km$^1$, which raises a critical demand for selecting circuit-breaker contact materials. A circuit-breaker, one of the key components in electrical power systems, is designed for making, breaking, as well as clearing the fault currents on-demand within a very short period (microseconds) to control and protect the other components in a circuit$^2$. The contacts, which are the key components of a circuit-breaker, play a decisive role in its overall performance, affecting the safety and reliability of the power transmission$^3$$^5$. An ideal contact material should possess the following merits: appropriate hardness, high electrical conductivity, high thermal conductivity, low contact resistance, and high resistance against electrical arc erosion.

Copper-tungsten (CuW) alloy is a pseudo-binary phase composite conventionally used in manufacturing circuit-breaker contacts$^6$. The CuW alloy enjoys the benefits held by Cu and W elements, such as maintaining favorable mechanical strength, high electrical arc erosion, and welding resistance due to the presence of W, while keeping excellent electrical and thermal conductivity as a result of the presence of Cu.

Advanced fabrication technology and adding reinforcement elements are effective strategies to improve the performance of electrical contact materials$^7$$^11$. Infiltration technology has been adopted for decades as the mainstream method for CuW contacts manufacturing. Nevertheless, the overall performance of the products is
limited by the uneven distribution of the Cu and W phases in the CuW alloy. Zhang et al fabricated Al2O3–Cu/15W and Al2O3–Cu/15W5Cr by vacuum hot-pressing sintering and internal oxidation technique [12]. The Al2O3–Cu/15W5Cr exhibits less mass change than Al2O3–Cu/15W due to the addition of the Cr element. Another ultrafine crystalline CuCr50 composite is prepared by spark plasma sintering process, which shows better arc erosion resistance than commercial materials [13]. However, the uniform distribution of Cu is still a difficult problem in the materials prepared by these methods.

As a reinforcing phase, Al2O3 possesses a high melting point, high hardness, and chemical stability, which could improve the mechanical strength and thermal expansion properties of Cu-based composites [14–16]. Lee et al [11] studied the effect of 100 nm Al2O3 on 100 kA pulsed arc erosion performance of W80/Cu–Cu2Al2O3, which shows enhanced performance with less mass loss after arc erosion test in vacuum. Ding et al [17] prepared nanoparticle Al2O3 (2wt%) reinforced copper-matrix composites with powder metallurgy method, demonstrating an electrical conductivity of 81% IACS, a hardness of 98 HV, and a 46% decrease of average wear losses. Tian et al [18] have prepared Cu-0.5vol% Al2O3 composites using internal oxidation at a softening temperature of 800 °C. The electrical conductivity of composite reaches 93% IACS in their study. Zhang et al [19, 20] have prepared Al2O3–Cu25W5Cr and Al2O3–Cu35W5Cr composites using vacuum hot-pressing sintering and internal oxidation process. The hardness of their testing samples was significantly improved, but with a trade-off of decline in electrical conductivity. Although there are many methods to fabricate CuW80 composite contacts, their performances still need improvement. It is necessary to optimize the preparation conditions to enhance their overall performances further.

In this paper, we reported the preparation of Cu@W80 powders by the chemical coating method. Spark plasma sintering (SPS) technology [21, 22] was then applied to synthesize the Al2O3/Cu@W80 composites with different Al2O3 contents (1wt%, 2wt%, 3wt%). The evolution in microstructure, mechanical properties, electrical conductivity, and vacuum arc erosion properties of Cu@W80 and Al2O3/Cu@W80 were systematically investigated and analyzed. The 3wt% Al2O3/Cu@W80 composite achieves the best overall performance. Our study paves an effective way to improve the performance of CuW80 contacts for the application in ultrahigh voltage power transmission.

### 2. Experiments

#### 2.1. Raw materials

The raw materials used in our study include tungsten, copper, and Al2O3 powders. The purity of the W and Cu powders is finer than 99.9%. The surface of the tungsten powder has a polyhedral form with an average grain size of around 5 μm; the Copper powder has a roughly spherical form with an average grain size of ∼2–3 μm. The optical characterization indicates that Al2O3 powder presents a flake morphology with 1 μm in thickness and 2 μm in diameter.

A chemical coating process was employed to prepare the Cu-coated W (Cu@W) powders. The W powders were first ultrasonically rinsed with 10 wt% NaOH solution for 10 min, followed by deionized (DI) water washing three times. Then, the powders were ultrasonically washed with 10 wt% HCl solution for 10 min, followed by another DI water washing three times. Finally, the powders were rinsed with ethanol and dried for the next step. The detailed processing parameters for preparing Cu@W powders are presented in Table 1.

The solution for the chemical coating of Cu was prepared with a magnetic stirrer to avoid thermal decomposition. After the coating process, the Cu@W powders were repeat-washed by DI water and ethanol, respectively, and dried by the freeze-drying method.

| Operating conditions | Processing parameters |
|----------------------|-----------------------|
| W powder | 20 g l⁻¹ |
| CuSO₄·5H₂O | 20 g l⁻¹ |
| Sodium Potassium Tartrate | 50 g l⁻¹ |
| Formaldehyde | 20 ml l⁻¹ |
| Dipyridine | 40 mg l⁻¹ |
| pH | 12 |
| Solution temperature | 40 °C |
2.2. Samples preparation

The Al$_2$O$_3$ powders with weight ratios of 1wt%, 2wt%, and 3wt% were added to the Cu@W powders to prepare the Al$_2$O$_3$/Cu@W composites. Each Al$_2$O$_3$/Cu@W mixture was stirred for 24 h using a V-type powder mixer. Then, the Al$_2$O$_3$/Cu@W composites were prepared by an SPS apparatus with the following processing parameters: sintering temperature: 1250 °C, sintering pressure: 30 MPa, holding time: 2 min. A total number of four samples were prepared: pristine Cu@W80, 1wt%, 2wt%, and 3wt% Al$_2$O$_3$/Cu@W80. The CuW80 composites were prepared with the aforementioned raw copper and tungsten powders via an infiltration method.

2.3. Methods for the performance characterization

A scanning electron microscope (SEM, Hitachi SU3600) was used to characterize the microscopic morphology of the prepared Al$_2$O$_3$/Cu@W80 powders. EDX analyses for elemental mapping were also carried out. A metallographic microscope (Nikon MA20) was applied for metallography observation. After electrical breakdown tests, a color laser scanning microscope (VK-9700 3D) was employed to analyze the powder’s 3D microscopic morphologies.

The crystal structure was determined by an x-ray diffractometer (PANalytical XPert PRO), in which Cu K$\alpha$ radiation with a fixed wavelength of 1.54056 Å was used as the x-ray source. The working voltage and current were configured at 40 kV and 40 mA, respectively. The sweeping angle ranges from 20° to 100°. The grain size of the copper after deposition was calculated using Slow Scanning Mode and Multi scanning Mode with a 446° sweeping angle coverage. The hardness measurements of the samples were performed with a Vickers Micro-Hardness Tester (Wilson VH1102). A type 7501 Eddy Current Conductivity Meter was used to measure the sample conductivity. The densities of the samples were calculated by practicing Archimedes Method.

The composition of a vacuum arc is quite different from other high-pressure arcs (SF$_6$ arcs, for example). The arc columns are made up of ionized gas from the arc’s surrounding ambient for high-pressure arcs. In contrast, the arcs burning in a vacuum chamber are composed of metal vapor boiled off from the electrodes, making the electrode material the major influencing factor.

The breakdown strength in a vacuum is one of the key performance indexes for the testing electrode material, which indicates the maximum electric field strength that the vacuum can sustain without breakdown at a given distance between electrodes. The breakdown strength could be calculated using the following formula:
where \( E_C \) is the average breakdown strength \((V \cdot m^{-1})\), \( E_i \) is the measured breakdown strength at the \( i \)-th measurement, \( U_i \) is the applied voltage at the \( i \)-th measurement \((V)\), \( d_i \) is the breakdown distance at the \( i \)-th measurement, and \( n \) is the total number of breakdowns.

In our study, each sample was subject to a total number of 10 breakdown tests. The voltage \( U_i \) and distance \( d_i \) were recorded each time for calculating individual breakdown strength \( E_i \). The stability of the dielectric strength was observed as well. The overall dielectric strength \( E_C \) was represented by the average value of \( E_i \). High-voltage circuit-breakers are often subject to extreme voltage stresses and current surges. In order to examine the stability of the contact material under such severe conditions, samples were tested in a vacuum chamber. Material performances were evaluated from the average breakdown strength, microscopic morphology features after vacuum arc erosion, surface roughness, and element distributions.

### 3. Results and discussion

#### 3.1. Characterization of the Al\(_2\)O\(_3\)/Cu@W80 powders

Figure 1 presents a back-scattered electron image and corresponding EDS elemental mapping of the Al\(_2\)O\(_3\)/Cu@W80 powders. It can be observed that the element distributed in those dark areas (figure 1(b) and (c)) contain enormous aluminum, indicating that those elements are from the added Al\(_2\)O\(_3\) powder. Moreover, both Al and Cu elements tend to distribute in a meshy form with a similar pattern. The benefit of this tendency is that the Al\(_2\)O\(_3\) powder could be dispersedly distributed among the Cu phase, which enlarges the Al\(_2\)O\(_3\)-Cu interface areas after sintering.
Figure 2 presents the XDR pattern of the Al$_2$O$_3$/Cu@W80 powder. Not only the Cu and W peaks are observed from the XDR spectrum, but the Al$_2$O$_3$ peaks are also identified. However, the peaks intensities of Al$_2$O$_3$ are rather weak, which could be attributed to the low adding ratio (3wt%).

3.2. Characterization of the Al$_2$O$_3$/Cu@W80 composites

Figure 3(a) shows a back-scattered electron image of the as-prepared 3wt% Al$_2$O$_3$/Cu@W80 composites. The light areas in the image indicate the W phase, whereas the surrounding dark areas indicate the Cu phase. From the EDS spectrum of an individual point (inset of figure 3(a)), it is confirmed that those dark matters embedded with the Cu phase are the added reinforcing Al$_2$O$_3$. The EDS mapping image in figure 3(b) shows uniform distribution of the W grains. The Cu grains were distributed in the form of mesh as fillers between W grains. The Al and O distributions overlaid (figures 3(c) and 3(e)), indicating that the Al$_2$O$_3$ particles were evenly distributed in the base material. The high-temperature sintering process did not alter the position of the Al$_2$O$_3$ particles.

| Al$_2$O$_3$ content (wt%) | 0   | 1   | 2   | 3   |
|--------------------------|-----|-----|-----|-----|
| Density (g cm$^{-3}$)    | 14.36 | 13.86 | 13.6 | 13.48 |

Table 2. Composite density versus Al$_2$O$_3$ adding contents.

Figure 5. The Al$_2$O$_3$ content dependence of hardness and electrical conductivity for Al$_2$O$_3$/Cu@W80 composites. (a) Hardness; (b) Electrical conductivity.

Figure 2 presents the XDR pattern of the Al$_2$O$_3$/Cu@W80 powder. Not only the Cu and W peaks are observed from the XDR spectrum, but the Al$_2$O$_3$ peaks are also identified. However, the peaks intensities of Al$_2$O$_3$ are rather weak, which could be attributed to the low adding ratio (3wt%).
This can be attributed to the fact that the Al$_2$O$_3$ particles were surrounded by melting copper and distributed around the tungsten particles together after copper solidified.

Figure 4 shows the microstructure images of Cu@W$_80$ composites with different Al$_2$O$_3$ contents measured using the scanning electron microscope in back-scattered mode. The results reveal that the black Al$_2$O$_3$ particles are diffusely distributed around the tungsten particles and embedded in the copper phase. The size of the tungsten particles is relatively homogeneous, and the refinement occurs mostly in the regions where Al$_2$O$_3$ is present. This phenomenon could be attributed to the alumina’s high melting point and hardness. The presence of Al$_2$O$_3$ particles severely inhibits the growth of the contact between the heavy tungsten particles during the sintering process. Consequently, the size of the tungsten powder is well-maintained.

Table 2 lists the relationship between composite density and the adding percentage of Al$_2$O$_3$. It can be found that the density of the composite decreases with increasing adding content. As the added Al$_2$O$_3$ particles become an obstruction to the flow of copper during sintering, many holes are formed, which is the main reason for the decrease in material density. Besides, the density of Al$_2$O$_3$ is smaller than the theoretical density of copper-tungsten alloys. A small amount of Al$_2$O$_3$ reinforcement will also slightly affect the composite density.

To ensure the accuracy of collected data, the hardness test samplings were taken from the edge to the center. The hardness results are presented in figure 5(a). It shows that the Al$_2$O$_3$ content has a significant effect on the

![Figure 6](image_url) Reinforcement effect on the breakdown voltages. (a) Cu@W$_80$ composites. (b) Al$_2$O$_3$/Cu@W$_80$ composites with 3wt% Al$_2$O$_3$.

![Figure 7](image_url) Comparison of the minimum breakdown voltage among CuW, Cu@W, and Al$_2$O$_3$/Cu@W$_80$ composites with different Al$_2$O$_3$ weight ratios. The line in red column bar represents the minimum value while that in white area shows the maximum value of composites.
hardness of the composite samples. It increases monotonously with the increasing adding content and reaches 273.1 HV at 3wt%. The conductivity, however, drops drastically (figure 5(b)) from 20.4 MS·m⁻¹ for the sample without adding Al₂O₃ down to 15.5 MS·m⁻¹ for the sample with 3wt% adding ratio, which is similar to 27% IACS [23].

Two mechanisms may explain the improvement of hardness observed in the Al₂O₃-reinforced samples. First, the resistance of the dislocation movement increases with the presence of dispersive Al₂O₃ particles at the Cu grains interface. Moreover, the mismatch of plastic deformation between the Cu matrix and hard Al₂O₃ particles is also a contributing factor. The finely dispersed Al₂O₃ has a strengthening effect on the copper matrix, reducing the amount of copper plastic deformation and increasing the hardness.

As for electrical conductivity, the decrease can be explained from the following aspects. First, the doped Al₂O₃ particles create holes in the matrix and inhibit the Cu flow during the sintering process. Therefore, the composite’s density decreases, as well as the conductivity. Besides, the doped Al₂O₃ particles bring more heterophase interfaces to the system, which increases the electron scattering. Finally, the rigid Al₂O₃ particles inhibit the growth of the W grains. The Al₂O₃ reinforced Cu increases the hardness but inhibits its fluidity. More heterophase interfaces are created, and the material’s electrical conductivity decreases as a result.

Figure 6 shows the breakdown voltage measured from the Cu@W80 composites (figure 6(a)) and the Al₂O₃/Cu@W80 composites with 3wt% Al₂O₃ (figure 6(b)). It can be found that the alloy sintered with Cu@W80 powder presents relatively unstable breakdown electric fields. The average breakdown strength finds itself at 1.50 × 10⁸ V·m⁻¹. The composite doped with 3wt% Al₂O₃, on the other hand, suggests a drop of the average breakdown strength to 1.12 × 10⁸ V·m⁻¹, with fluctuations as well.

According to figure 7, the minimum breakdown voltage exhibits a drop with increasing Al₂O₃ content compared with the Cu@W80 composites. Nevertheless, even the composite with the highest adding ratio (3wt% Al₂O₃, 1.12 × 10⁸ V·m⁻¹) stands a distinct advantage over the pure Cu@W80 composites manufactured via the traditional infiltration method (4.6 × 10⁷ V·m⁻¹).

3.3. Performance under vacuum arc erosion of Al₂O₃/Cu@W composites
The CuW80, Cu@W80 and 3wt% Al₂O₃/Cu@W composite samples were selected for comparison. Figure 8 shows the microscopic morphology of the samples taken at a low magnification. From figures 8(a)–(c), it can be found that an equal chance of arc erosion and sputtering was observed because the Cu@W80 and Al₂O₃/Cu@W composite composites prepared via the chemical coating method barely form any Cu-rich areas compare to the CuW80. On the other hand, for the 3wt% Al₂O₃/Cu@W composite, the sputtering was formed evenly in all directions, and a well-regulated morphology could be observed at the erosion area. What’s more, the size of arc-eroded area is smallest among three types of composites, which indicates less ablation during the arc erosion process.

Figures 8(d)–(f) exhibit the EDS mapping of these three composites in the arc-eroded regions. The CuW80, Cu@W80 and Al₂O₃/Cu@W80 composites show approximately the same elements distribution. In both images, W elements are the majority remaining (marked as green pixels) at the most severely eroded areas. The
Cu elements are mostly eroded or sputtered around, gathering at the edge of eroded areas (marked as red pixels). For the Al₂O₃ added composite sample, Cu elements are mostly eroded at the central area and pile up in a heap at the edge. Al elements gather in the rim outside the central area (marked as blue pixels).

The vacuum arcing behavior was further investigated by analyzing the surface roughness and microscopic morphology of the arc eroded areas. Figure 9(a) shows the backscattered electron image of the 3wt% Al₂O₃/Cu@W sample after subject to vacuum arc erosion tests. The area exposed to arc erosion is relatively flat in general. Nevertheless, the central region presents significant unevenness and forms a sputtering-like appearance. The experimental result does not find very deep erosion pits after the sample has been subject to breakdown tests for 10 times. A 3D-laser microscope analysis was carried out and presented in figure 9(b). It can

![Figure 9. Vacuum arc erosion test result for 3wt% Al₂O₃/Cu@W composite. (a) Backscattered electron image. (b) Line roughness.](image)

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![Figure 10. Characterizations of the erosion pits. Surface morphologies of Cu@W80 (b) and 3wt% Al₂O₃/Cu@W80 composites (b) after vacuum arc erosion test. (c) EDS spectrum obtained from the red mark in figure 10(b).](image)
be seen that the height in the central region remains at the same height level as the substrate surface, except that there is a radial accumulation of material at the edges, indicating that the material has a strong resistance to arc erosion.

Figure 10(a) and b exhibit the erosion pits of Cu@W alloy and 3wt% Al2O3/Cu@W. It can be found that the erosion pits are shallow and randomly distributed for the Cu@W alloy (figure 10(a)). In contrast, for the 3wt% Al2O3 added composites, the erosion pits are deeper (figure 10(b)), and each of the pits contains a large number of Al elements (figure 10(c)). These results reveal that electrical discharges are drawn primarily at those spots where Al2O3 are added. Hence, it proves that the added Al2O3 can effectively guide and diffuse the arcs in a vacuum. This phenomenon could be attributed to the variation of work function. As is known, the work function of Al2O3 (3.9 eV) is lower than that of Cu (4.36 eV) and W (4.6 eV). Additionally, the distribution of rigid Al2O3 particles in the Cu phase forms abundant hetero-phase interfaces between Al2O3 and Cu, which plays an active role in dispersing the arc, guiding the ablation, and improving the stability of the arc.

4. Conclusion

In conclusion, we reported Al2O3/Cu@W composites with improved hardness and anti-arc erosion performance, prepared by chemical coating and SPS methods. The Al2O3 is homogenously distributed in the matrix and can refine the tungsten particles, thus increasing the hardness of the material by 40.8% compared to those without adding Al2O3. Despite the decrease in material density, the electrical conductivity and breakdown strength of the Al2O3/Cu@W composites reach 15.5 MS m−1 and 1.12 × 108 V m−1, respectively. However, the fluctuation was not significant, and the breakdown strength was still greater than that of the pure Cu W alloy (manufactured via conventional infiltration method) at the maximum added ratio of Al2O3. This could be due to the lowest work function of Al2O3 among the three compounds and increased hetero-phase interfaces. Our study reveals that the Al2O3/Cu@W80 composite can be used as a promising candidate for contact materials in ultrahigh voltage power transmission.

Fund

This work is financially supported by the State Grid Corporation of China Science and Technology Foundation (5500-202058474A-0-0-00).

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

Conflicts of interest

There are no conflicts to declare.

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