Erosion behavior and mechanism of Cu-B₄C composites under arc discharge in different atmospheres

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Abstract
Ceramic particle-reinforced materials are an important part of high-performance contact materials because of the excellent performance in resistance to arc erosion. In particular, B₄C is the ideal choice for the preparation of high-performance electrical contact materials because of its excellent physicochemical properties. In this paper, Cu-B₄C composites were prepared by hot-press sintering technology to illustrate the arc erosion behavior of Cu-B₄C composites in different atmospheres at high voltages. The erosion morphology and composition of Cu-B₄C composites after erosion in air, carbon dioxide and sulfur hexafluoride atmosphere at 8kV were studied. The different erosion mechanisms of Cu-B₄C composites in air, carbon dioxide and sulfur hexafluoride atmospheres were systematically discussed. The results showed that the Cu-B₄C composites exhibited inhomogeneous erosion in all three atmospheres, and the erosion was mainly concentrated in the region around the B₄C particles. In air, the Cu-B₄C composites were most severely eroded, but showed better erosion resistance in carbon dioxide and sulfur hexafluoride. The experimental atmosphere decomposed and reacted with copper on the cathode surface at high temperatures, while B₄C maintained a good structure after erosion.

1. Introduction

Electrical contact materials are the main components used in electrical products, which are responsible for switching the currents on and off [1]. However, during the operation of the equipment, the arc generated between the electrodes produces an ablative effect on the cathode surface, leading to melting, evaporation, splashing and material transfer of the electrode material, which in turn can affect the material properties and lead to material failure [2, 3]. Therefore, the property and quality of electrical contact materials are directly related to the reliability of equipment operation [4]. Electrical contact materials are required to have good electrical and thermal conductivity in addition to strength, resistance to welding and resistance to arc erosion. Typically, they consist of a high conductivity matrix and a high melting point component with high wear resistance and resistance to arc erosion [5, 6].

Copper is considered one of the best choices for electrical contact materials because of its excellent thermal conductivity (401 W mK⁻¹) and electrical conductivity (5.96 × 10⁷ S m⁻¹), in combination with its low cost and ease of processing [7, 8]. However, the poor hardness of copper and its tendency to oxidize at high temperatures limit its use as an electrical contact material [9]. It has been reported that the high-temperature strength of copper alloys can be improved by adding a low volume fraction of well-dispersed ceramic particles, which can effectively improve the arc erosion properties without severely damaging the electrical conductivity of the material [10, 11]. Wang et al [12] found that the fine Al₂O₃ particles resulted in relatively shallow erosion pits in the Cu-Al₂O₃ composites. Yang et al [13] found that the addition of WC particles improved the breakdown
strength and reduced the chopping current of the W-Cu alloy, and the surface of the W-Cu alloy with WC addition had less copper sputtering and pitting after erosion.

Although the ceramic particles help to improve the welding and wear resistance of the material during the initial stages of arc erosion, the ceramic particles bond poorly to the copper matrix and tend to flake off from the copper matrix. In addition, the ceramic particles undergo phase transformations during the erosion process, which will lead to a continuous degradation of the quality and conductivity of the electrical contact material [9]. Wang et al [14] found a large number of small and deep erosion pits around the erosion centers, which were caused by a large number of Al₂O₃ particles floating to the surface. Huang et al [15] found that after arc erosion of Cu-Ti₃AlC₂ composites in air, Ti₃AlC₂ particles oxidized and decomposed into TiO₂ and Al₂O₃, and these oxide particles attached to the material surface would affect the ablation resistance of the material.

In order to ensure the reliability of the long-term performance of copper-based electrical contact materials, ceramic materials should have higher thermal and chemical stability. In engineering applications, B₄C is favored for its outstanding properties such as low density, high melting point, high hardness, excellent resistance to chemical erosion and high wear resistance. Since boron carbide ceramic has higher melting point and chemical stability than oxide ceramic, its hardness even outperforms diamond and boron nitride at high temperature, which can improve the high temperature strength of the matrix [16]. Shu et al [17] found that adding 15 wt% of B₄C to the copper matrix resulted in a hardness of 86 HBW, which is 79.2% higher than that of pure copper, effectively improved the wear resistance of the copper matrix. Bai et al [18] found that when the volume fraction of B₄C is 40%–70%, composites with relatively low coefficient of thermal expansion in combination with an efficient thermal conductivity will be obtained. Tian et al [19] found that the addition of appropriate amounts of B₄C particles to copper-based graphite composites effectively increased the hardness and compressive yield strength and reduced the porosity and wear loss of composites. Moreover, the excellent chemical inertness and thermal stability of B₄C ensure that no compounds are generated at high temperatures that would decrease the electrical properties of the material, so it is considered a good candidate for the reinforcement phase of metals, ceramics and plastic matrixes [20–22].

Although a lot of researches have been conducted on the preparation process, high temperature performance and wear resistance of B₄C particle-reinforced copper matrix, there are few studies on the relationship between the microstructure and arc erosion behavior of Cu-B₄C composites in different atmospheres [23–25]. The aim of this paper is to prepare superior performance Cu-B₄C composites by hot-pressed sintering method and to investigate the arc erosion behavior and erosion mechanism of Cu-B₄C composites in air, carbon dioxide, and sulfur hexafluoride atmospheres.

2. Experimental

2.1. Fabrication of Cu–B₄C composites

First, B₄C powder (99% purity, average particle size of 38 μm) and Cu powder (99.95% purity, average particle size of 38 μm) were mixed in a grinding bowl and mechanically stirred for 4 h to obtain the uniformly mixed powders, wherein the B₄C powders volumetric fraction was fixed at 10%. Then put the mixed powder into a high-strength graphite mold for cold pressing. Subsequently, the graphite mold was put into a vacuum hot pressing furnace (ZT–40–20TI) as shown in figure 1(a) and heated to 900 °C under argon protection at the pressure of 30 MPa and held for one hour, and then cooled to room temperature in the furnace.

The obtained samples were cut into blocks of 10 mm × 10 mm × 3 mm (L × W × H) by wire cutting, and the block samples were polished and cleaned to obtain samples that meet the experimental requirements. Subsequently, The composition of the phases was characterized by x-ray diffraction (XRD, X-pert PRO MPD). The morphology and structure of Cu-B₄C composites were observed by field scanning electron microscopy (FE-SEM, SU8020). The density of Cu-B₄C composites was measured in accordance with Archimedes’ principle, while the hardness was measured with a Brinell hardness tester (HBV–30A), and the conductivity was measured with a two-arm bridge method resistance tester.

2.2. Physical and mechanical properties tests

The relative density (Δ) of the Cu-B₄C material can be calculated by formula:

$$\Delta = \frac{\rho}{\rho_0}$$  \hspace{1cm} (1)

Where ρ is actual density of samples and ρ₀ is theoretical density. The actual density of the sample can be measured in accordance with Archimedes’ principle, and the theoretical density (ρ₀) of the sample can be calculated according to formula:
\[ \rho_0 = \rho_1 \varphi_1 + \rho_2 \varphi_2 \]  

Where \( \rho_1 \) is the density of Cu, \( \varphi_1 \) is the volume fraction of Cu; \( \rho_2 \) is the density of B4C, \( \varphi_2 \) is the volume fraction of B4C.

The hardness of nonferrous materials is usually measured by force loading Brinell hardness testers. Namely, apply a normal force load 10 kg on the surface of the sample surface, hold the pressure for 30s, unloading the material, then use the average stress of the indentation spherical surface area as the Brinell hardness \( (HB) \) value of the measured sample [26]. The value of Brinell hardness can be obtained by formula:

\[ HB = \frac{0.204P}{\pi D(D^2 - d^2)} \]  

Where \( P \) is the applied load (kg), \( D \) is the diameter of steel ball (mm), and \( d \) is the diameter of the circular indentation (mm). The sample was measured for five points, and the Brinell hardness of the material was the average value of five data.

A direct current two-arm bridge was used to measure the electrical resistivity, electrical conductivity \( (w) \) can be expressed by the following formula [27]:

\[ w = \frac{IL}{US} \]  

Where \( I \) is the current through the sample (A), \( L \) is the distance between two electric potential needles (mm), \( U \) is the voltage between two electric potential needles (mV), \( S \) is the cross-sectional area of the sample (mm²).

### 2.3. Arc erosion test

Figure 1 (b) shows the diagram of the experimental device used for arc erosion. Figure 1(c) shows the internal structure of the airtight chamber, with Cu-B4C composite as the cathode and tungsten rod as the anode, and the same process parameters as the actual working conditions were used to perform the erosion experiments on the samples. The chamber inside the device was pumped into vacuum with a vacuum diffusion pump, and then
filled with different experimental atmospheres as the extinguishing medium until the pressure reached the standard atmospheric pressure. A DC voltage of 8 kV was applied as a load voltage between the two electrodes, and the cathode was controlled by a stepper motor controller (DM422C) that moved slowly toward the anode at a speed of 0.3 mm min\(^{-1}\). When the distance between the electrodes was small enough, the gas medium decomposed to produce an arc, and then the distance between the electrodes was recorded as the discharge distance. A digital storage oscilloscope (ADS1102CAL) was used to record the breakdown current and the current duration when the arc was generated.

The erosion morphology of Cu-B\(_4\)C composites was obtained using field scanning electron microscopy (FE-SEM, SU8020) and three-dimensional laser scanning confocal microscopy (3D-LSCM, VK-X250). The discharge state was recorded using a high-speed camera (FASTCAM Nova S16), which has a framing rate of 120,000 fps. The composition of the erosion region was analyzed by energy spectroscopy (EDS) and Raman Spectroscopy (LABRAMHR).

**3. Results**

**3.1. Microstructure and physical propriety of Cu-B\(_4\)C composites**

Figure 2 shows the micrographs and XRD patterns of the original powders as well as the Cu-B\(_4\)C composites. It can be seen that the Cu powders have the dendritic shapes, while the B\(_4\)C particles have angular and irregular shapes. After mechanical mixing, the particle size of Cu powders becomes smaller and B\(_4\)C is uniformly distributed in Cu powders. A clear interface between the two phases can be observed in the Cu-B\(_4\)C composites. The light gray area indicates the Cu matrix, the irregularly shaped dark gray particles are B\(_4\)C particles, and the B\(_4\)C particles are uniformly distributed in the Cu matrix without pores and cracks. Figures 2(e)–(f) shows the x-ray diffraction spectra of the mixed powders and Cu-B\(_4\)C composites, only the copper peak and the B\(_4\)C peak can be detected, which indicates that there is no reaction between B\(_4\)C and Cu.

Table 1 summarizes the physical properties of the Cu-B\(_4\)C composites. During hot-pressed sintering, the flow of copper forms a continuous copper network around the B\(_4\)C particles, and the density of the sample is up to 99.2%. Moreover, this continuous copper network reduces the agglomeration phenomenon of B\(_4\)C particles, thus reducing the scattering of electrons by B\(_4\)C particles, and its electrical conductivity reaches 82.83% IACS. The Brinell hardness of the Cu-B\(_4\)C composite reaches 67.7 HB. The increase of matrix hardness can be attributed to
two aspects. On the one hand, because the hardness of B$_4$C particles is much higher than Cu, the addition of B$_4$C can significantly improve the hardness of Cu matrix. On the other hand, the hardness of the material increases due to the uniform distribution of fine B$_4$C particles in the Cu matrix producing a pegging effect that hinders the movement of dislocations [28].

3.2. Arc discharge behaviors of Cu-B$_4$C composites in different atmospheres

Figure 3 shows the current-time curves of Cu-B$_4$C composites at 8 kV in air, carbon dioxide and sulfur hexafluoride atmospheres, respectively. In figures 3(a)–(c), the current value increases instantaneously to a peak with the generation of an arc between the electrodes, and the maximum current value at the red arrow is the breakdown current. The current gradually decreases, and the current value at the black arrow means the chopping current. The time from maximum current down to the chopping current is the arc life. In figure 3, the arc duration in air, carbon dioxide and sulfur hexafluoride atmospheres were 31.464 ms, 30.72 ms and 26.944 ms, respectively. It can be seen that the arc duration in carbon dioxide atmosphere is about 1 ms less than that in air, while the arc duration in sulfur hexafluoride atmosphere is much shorter. The arc duration shows that among the three atmospheres, sulfur hexafluoride has the best arc extinguishing performance, followed by carbon dioxide, and the worst in air.

Arc energy is one of the important electrical parameters of the arc. In general, the arc will severely erode the material as the arc energy increases. Arc energy can be calculated by the formula [29]:

$$W = \int U di dt$$

Where $W$ is the arc energy (J), $U$ is the load voltage (kV), $i$ is the breakdown current (A), and $t$ is the arc duration (ms). Seen from the above formula, the arc energy is related to the voltage, current and arc life. It can be seen that the arc energy and arc duration have the same trend, decreasing in the order of air, carbon dioxide and sulfur hexafluoride.
In our experiments, it represents the diffusion of the material surface. Figures 4 show arc erosion is a complex physicochemical process that changes the morphology and compositions of the area of Cu-B4C composites under air, carbon dioxide and sulfur hexafluoride. This indicates that the erosion probability of Cu-B4C composites decreases in the order of air, carbon dioxide and sulfur hexafluoride. This is due to the fact that there is no chemical reaction between Cu and B4C during the sintering process and pure copper has reached 44 ppm by weight at 1353 K.

Moreover, the heights are not uniform in the eroded areas, suggesting that arc occurs at different atmospheres. The discharge distance is 0.32 cm in air atmosphere, 0.22 cm in carbon dioxide atmosphere, and 0.09 cm in sulfur hexafluoride atmosphere. The calculation results are shown in table 2, which shows that the breakdown strength increases in the order of air, carbon dioxide, and sulfur hexafluoride, with values of 2.50 × 10^6 J, 3.64 × 10^6 J, and 8.89 × 10^6 J, respectively, which is the opposite of the arc duration and arc energy. This indicates that the erosion probability of Cu-B4C composites decreases in the order of air, carbon dioxide and sulfur hexafluoride.

3.3. The morphology and composition of Cu-B4C composites after arc erosion in three atmospheres

Arc erosion is a complex physicochemical process that changes the morphology and compositions of the material surface. Figures 4(a)–(c) show that the Cu-B4C composites exhibit different overall morphological characteristics in the three atmospheres. Under the high temperature of the arc, a molten pool of metal is formed on the surface of the cathode. Under the effect of electromagnetic stirring, the molten pool flows from the center to the edge. Under the high-energy impact of the arc, the central erosion area is severely damaged, covered with pits and bulges, while the erosion edge is less damaged with splash particles. The area where erosion occurs in air shows an irregular shape and the erosion area is significantly larger than the other two atmospheres. In the carbon dioxide atmosphere the erosion area becomes regular and the erosion area becomes smaller, but it can be seen that the erosion is more severe in the central areas than in the edge areas. The shape of erosion area in sulfur hexafluoride atmosphere is nearly circular, and the erosion area is the smallest among the three atmospheres.

The eroded surfaces of the Cu-B4C materials in the three atmospheres were reconstructed by 3D LSCM, as shown in figures 4(d)–(f). The unaffected surface is used as the baseline, with the red parts indicating bulges and the dark blue parts indicating pits or pores. Among the three atmospheres, the central area of the molten pool is lower than other areas, and the edge of the molten pool is raised due to the accumulation of molten copper. Moreover, the heights are not uniform in the eroded areas, suggesting that arc occurs first in some parts and then moves to other parts, which leads to inhomogeneous erosion.

To further clarify the effect of B4C particles on the arc erosion behavior, the morphology of erosion central area of Cu-B4C composites under air, carbon dioxide and sulfur hexafluoride atmosphere was further analyzed by SEM.

3.3.1. In air atmosphere

Figure 5 shows the microstructure of the sample after erosion in air. In figure 5(a), the exposed Cu matrix is relatively smooth after being eroded, while obvious crevice appears between the B4C particle and the Cu matrix. This is due to the fact that there is no chemical reaction between Cu and B4C during the sintering process and only a weak mechanical bond exists, so the phase boundary is easily and severely damaged by the force of the arc.

Air is mainly composed of nitrogen and oxygen, but it is mentioned that nitrogen is insoluble in solid and liquid copper below 1673 K, and its solubility is only 1.6 mass ppm at 2443 K. Therefore, We can speculate that most of the gas dissolved in the molten copper at high temperature is oxygen. During the cooling process, the solubility of oxygen in molten copper decreases as temperature decreases, the oxygen dissolved in the copper escapes and forms pores on the cathode surface. In figure 5(c), the copper liquid is limited by the uniformly distributed B4C particles that cannot splash outward and forms an irregular morphology around the B4C after cooling. Enlarging

| Atmospheres        | Air       | Carbon dioxide | Sulfur hexafluoride |
|---------------------|-----------|----------------|---------------------|
| Breakdown current(A)| 32.00     | 31.20          | 30.80               |
| Arc duration(ms)    | 31.46     | 30.72          | 26.94               |
| Discharge distance(10^-3 m) | 3.20     | 2.20          | 0.90                |
| Breakdown strength(10^6 V m^-1) | 2.50     | 3.64          | 8.89                |

Where E is the breakdown strength (V m^-1), U is the load voltage (V), and d is the distance between the electrodes during the arc discharge (m). Because the voltage is fixed to 8 kV, the discharge distance will change in different atmospheres. The discharge distance is 0.32 cm in air atmosphere, 0.22 cm in carbon dioxide atmosphere, and 0.09 cm in sulfur hexafluoride atmosphere. The calculation results are shown in table 2, which shows that the breakdown strength increases in the order of air, carbon dioxide, and sulfur hexafluoride, with values of 2.50 × 10^6 J, 3.64 × 10^6 J, and 8.89 × 10^6 J, respectively, which is the opposite of the arc duration and arc energy. This indicates that the erosion probability of Cu-B4C composites decreases in the order of air, carbon dioxide and sulfur hexafluoride.
the rectangular area in figure 5(c), cracks appear between the B₄C particles and the copper matrix, which are caused by the different thermal expansion coefficients of copper and boron carbide. The droplets in figure 5(e) were analyzed by EDS, and the droplets consisted mainly of 48 at% Cu and 52 at% O. As the atomic ratio of Cu to O is close to 1:1, it can be concluded that Cu was oxidized during the erosion, leading to the formation of CuO. Figure 5(g) shows the Raman spectrum of the Cu- B₄C composites after air erosion. The Raman peak at 270 cm⁻¹ can be attributed to the main characteristic peak of B₄C [34]. In addition, the main characteristic peaks at 295 cm⁻¹, 343 cm⁻¹ and 630 cm⁻¹ can be attributed to CuO [35]. This result indicates that the B₄C particles maintain a good structure without decomposition, while copper is oxidized after arc erosion.

3.3.2. In carbon dioxide atmosphere
As showed in figure 6(a), the surface of the eroded copper matrix is smooth in the carbon dioxide atmosphere. Compared with the air, the size of the spattered particles in the erosion area is much smaller because of the lower arc energy, and there is no crevice around the B₄C particles. However, the splashed copper in the melt pool stays on B₄C particles and forms bulges of different sizes. In figure 6(b), it can be observed that the copper solidified on the B₄C particles and then cracks were formed on the surface due to the different thermal expansion coefficients of copper and Boron Carbide, which generate stress concentrations during rapid cooling at high temperatures. The ability of copper to dissolve gas increases with increasing temperature, and the arc produces less heat in CO₂, so less gas is dissolved in the melt pool. Figure 6(c) is an enlarged picture of the rectangle in figure 6(b), which shows a reduction in the number and size of pores on the B₄C particles compared to the eroded morphology in
Figure 5. Microstructure and element consisted of the Cu-B$_4$C composites after arc erosion in air atmosphere. (a) Erosion central area; (b) Enlarged image of the yellow rectangle in (a); (c) Irregular shape of copper around B$_4$C particles; (d) Enlarged image of the yellow rectangle in (c); (e) Splash droplets; (f) EDS of the spattered droplet; (g) Raman spectrum of the arc erosion area of Cu-B$_4$C composites in air atmosphere.
air. Figure 6(d) is the EDS analysis of the solidified droplet in figure 6(c), suggesting that CO₂ decomposed at high temperature to produce O, which formed CuO with Cu and finally solidified on the B₄C particles.

In figure 6(e), the characteristic Raman peaks of B₄C (270 cm⁻¹) and CuO (609 cm⁻¹, RRUFID: R120076) [36] appear after erosion in CO₂, indicating that B₄C does not decompose in this atmosphere, and copper is oxidized.

3.3.3. In sulfur hexafluoride atmosphere

Figure 7 displays the typical morphology of Cu-B₄C composites after arc erosion in sulfur hexafluoride atmosphere. Compared with other atmospheres in this experiment, figure 7(a) shows that only some droplets stick to the surface of the B₄C particles after erosion, but there is a clear bulge next to the B₄C particles. There are no obvious cracks and pores on the surface of the copper matrix. Figure 7(b) shows the presence of multiple coral-like structures within the eroded region due to the excellent arc extinguishing properties of the sulfur hexafluoride atmosphere, which absorbs the heat generated by the arc and increases the viscosity of the melt pool, so that the droplets formed by gravity tend to solidify before sputtering outward. As the discharge distance

Figure 6. (a) Microstructure of central area of Cu-B₄C composites after arc erosion in carbon dioxide atmosphere; (b) Bulge morphology on B₄C particles; (c) Enlarged image of the yellow rectangle in (b); (d) EDS of the spattered droplet; (e) Raman spectrum of the arc erosion area of Cu-B₄C composites in carbon dioxide atmosphere.
in sulfur hexafluoride atmosphere is shortened, the surface of the cathode is eroded by the heat and undergoes strong thermal expansion, and then shrinks as the temperature decreases, resulting in cracks on the surface between these coral-like structures [37]. Figure 7(c) shows the sputtered particle formed in the sulfur hexafluoride atmosphere, whose EDS result is shown in figure 7(d), mainly composed of Cu, F and S. The results show that SF₆ decomposes at high temperature, while fluorine and sulfur are retained by reacting with molten copper.

The Raman spectra of Cu-B₄C composites after erosion in sulfur hexafluoride is shown in figure 7(e). The Raman peaks appearing at 220 cm⁻¹, 261 cm⁻¹ and 298 cm⁻¹ correspond to CuF₂ [38], and the Raman peak observed at 932 cm⁻¹ is consistent with the Raman shift of CuS according to RRUFFID:R060306. The above Raman results demonstrate the decomposition of SF₆ and the presence of CuF₂ and CuS, which is consistent with the EDS results.
4. Discussion

The arc is a critical factor in the erosion of material surfaces. In order to have a better understanding of the characteristics of the arc, we used a high-speed camera to observe the whole process of the arc from the formation to the extinction. In figures 8(a)–(c), there is a bright arc between the electrodes at the moment of gas breakdown, and the arc column becomes thicker from 0.011 ms to 0.113 ms. Figures 8(d)–(h) show the appearance of a purple light around the arc column, and the arc near the cathode surface is brighter compared to the other regions. As the arc burns, the brightness of the arc column gradually decreases, indicating that the arc energy gradually decreases. The contact point of the arc on the cathode moves, and the splitting of the arc foot can also be observed in figures 8(l)–(m). Finally, the concentration of the conducting medium between the electrodes is insufficient to sustain the burning of the arc, and the brightness of the arc gradually decreases until it disappears.

During the arc burning process, most of the arc energy is transferred to the cathode surface in the form of heat, resulting in the melting of the material surface and the formation of various erosion forms. In all three atmospheres, the erosion is inhomogeneous in the eroded region and may accelerate the failure of the cathode material. Therefore, the inhomogeneous erosion mechanism of Cu-B₄C composites is proposed to study the erosion characteristics of Cu-B₄C composites in different atmospheres from the microscopic level. To better describe this mechanism, a schematic diagram is given in figure 9.

In figure 9(a), the electric field intensity near the surface of the cathode increases as the cathode is closer to the anode. In this case, since there is only a mechanical bond between the B₄C particles and the copper matrix, the interface between them is easily damaged, allowing electrons to escape from the tiny regions around the B₄C particles. Under the influence of electric field, the electrons escaping from these regions move toward the anode at high speed, and some gas molecules and electrons are ionized during the collision. These electrons and positive ions form a conductive channel between the electrodes, leading to an arc between the electrodes.

Figure 8. Optical images of an arc from formation to extinction captured by a high-speed camera in air atmosphere. (a) 0 ms, (b) 0.011 ms, (c) 0.113 ms, (d) 0.783 ms, (e) 0.929 ms, (f) 1.178 ms, (g) 1.535 ms, (h) 3.347 ms, (i) 5.015 ms, (j) 7.545 ms, (k) 10.375 ms, (l) 13.533 ms, (m) 16.891 ms, (n) 19.721 ms, (o) 25.530 ms, (p) 31.325 ms.
The cathode surface melts under the bombardment of the high-energy arc, forming the molten pool in figure 9(b). Under the combined effect of vapor pressure and electromagnetic force generated by the arc, the droplets continuously splash outward. As the time of arc action on the material surface increases, the temperature of the cathode surface further increases and the melt pool area becomes larger. At this point, the heat transfer process within these areas is more active than in other areas due to the presence of the melt pool. If the arc stays a little bit longer, a considerable amount of evaporation occurs, which deepens the degree of regional erosion. However, the arc does not always erode a point, but moves rapidly over the cathode surface [39]. Due to the high thermal stability and high hardness of the B\textsubscript{4}C, and uniform distribution in the copper matrix, which has a blocking effect on the flow of the copper melt. Thus, in figure 9(d), various erosion patterns, such as bulges, cracks and craters, are formed around the B\textsubscript{4}C particles after solidification of the melt pool. [40]

Under the same conditions, the vapor pressure is proportional to the cathode temperature, which comes mainly from the heat transfer of the arc. Because the arc energy in air is highest among the three atmospheres, it can produce higher vapor pressure and stronger cathode surface bombardment [41]. In general, the arc has a large kinetic energy from the moment of triggering to the stable burning stage, which constantly bombards and moves on the cathode surface and causes inhomogeneous erosion. In the stable burning stage, most of the arc energy is transferred to the cathode surface in the form of heat, and the surface of the Cu matrix, which constitutes most of the cathode material, is oxidized to CuO [42]. Under vapor pressure, droplets tend to splash and deposit on the surface of the B\textsubscript{4}C particles. The arc lifetime in air is 31.46 ms, and the arc has sufficient time to erode the cathode surface, so the cathode surface has the largest erosion area and the most severe erosion inhomogeneity.

While in carbon dioxide atmosphere, when the temperature is higher than 2200 K, CO\textsubscript{2} will partially consume the arc energy to decompose into O\textsubscript{2} and CO, reducing the heat flow from the arc input to the cathode surface. At the moment of arc discharge, a chemical reaction occurs between O\textsubscript{2} and the copper matrix, and CuO is generated on the cathode surface. CO\textsubscript{2} has good electronegativity and weak adsorption of electrons, which gives it certain insulating properties. The current interruption performance of CO\textsubscript{2} is better than air, which makes the arc burning time shorter than in air, and the area of arc erosion becomes smaller, alleviating the inhomogeneity of erosion. [43]

Since the breakdown strength of sulfur hexafluoride is three times higher than that of air, this makes it more difficult for sulfur hexafluoride to be broken through and generate an arc, thus reducing the possibility of arc
erosion on the cathode surface. In addition, the thermal conductivity of sulfur hexafluoride increases with increasing temperature, and the high arc temperature it absorbs thus reduces the arc energy acting on the cathode surface and reduces the copper spattering caused by arc bombardment, which explains the absence of molten droplets forming protrusions on the B₄C particles. In addition, sulfur hexafluoride has strong electronegativity, which will consume energy to decompose into F and S, where both F and SF₆ will adsorb some electrons and reduce the arc energy. It is worth mentioning that the sulfur ions and fluorine ions formed by decomposition will recombine to form sulfur hexafluoride, which will rapidly restore the electrical insulation of the experimental atmosphere and accelerate the extinguishing of the arc, thus reducing the damage of the arc to the cathode. [44].

5. Conclusion

Here, we investigated the arc erosion behavior of Cu-B₄C composites in air, carbon dioxide and sulfur hexafluoride atmospheres at 8 kV. We analyzed the arc parameters and characteristics, microstructure of the eroded surface, compositional changes. The mechanisms of inhomogeneous erosion in different atmospheres were also proposed. The conclusions of the study are summarized as following:

(1) The arc energy and arc duration are the highest in air atmosphere, and decrease in the order of carbon dioxide and sulfur hexafluoride. The breakdown strengths of the three atmospheres change in the opposite order to the arc life.

(2) The morphology of the samples under the three atmospheres was observed, and the erosion area and erosion inhomogeneity of the samples gradually decreased in the order of air, carbon dioxide and sulfur hexafluoride. The microscopic morphology of the eroded areas was observed, which revealed that the cracks, a large number of bumps and pores appeared on the surface of the samples in air and carbon dioxide. In the sulfur hexafluoride atmosphere, coral-like morphology and microcracks appeared on the surface of the samples, and the quantity of bumps and spatters decreased.

(3) In both air and carbon dioxide atmospheres, Cu is oxidized to form CuO. In sulfur hexafluoride atmosphere, Cu is formed as CuF₂ and CuS. B₄C particles maintain a good structure during erosion.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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