Research Article

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Arc erosion behavior of TiB₂/Cu composites with single-scale and dual-scale TiB₂ particles

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Abstract: Arc erosion behaviors of TiB₂/Cu composites with single-scale and dual-scale TiB₂ particles fabricated by powder metallurgy were studied. It was revealed that the dual-scale TiB₂/Cu composites had fewer structure defects compared with the single-scale TiB₂/Cu composites, and TiB₂ particles with different size were uniformly distributed in the copper matrix. When the ratio of 2 μm over 50 μm TiB₂ particles is 1:2, the density of TiB₂/Cu composite is 98.5% and shows best mechanical and thermal properties. The arc duration and energy of TiB₂/Cu composites increase with the increase of electric current in contact material testing. Compared with the single-scale TiB₂/Cu composites, the arc erosion of dual-scale TiB₂/Cu composite with 2 μm+50 μm (1:2) TiB₂ was slighter. The anode bulge area and cathode erosion pit of dual-scale TiB₂/Cu composite was smaller. The dual-scale TiB₂ particles optimize the microstructure and thermal stability of the composite, which is conducive to alleviating arc erosion. The synergistic effect of different sized TiB₂ particles in the matrix improved the arc erosion resistance of TiB₂/Cu composite during arcing.

Keywords: dual-scale; TiB₂/Cu composites; arc erosion; thermal stability

1 Introduction

Copper matrix composites, which show wide application prospect in the field of transportation, power and so on due to their excellent conductivity, mechanical properties and thermal stability, have been attracting much attention [1–4]. With the rapid development of transportation, power, communication and other industries, the requirement of material performance is increasing constantly. For example, the level of transmission voltage is continuously improved. Higher transmission voltage would lead to higher temperature and more severe arc erosion of high voltage switch components. The properties of high voltage switch components material directly affect their service life and stability. Thus, developing copper matrix composites with good properties and arc erosion resistance is the key to solve the above problems [5–7].

Fibers, nanotube and ceramic particles are commonly used reinforcements in composites [8–10]. TiB₂ are widely concerned as a stable ceramic material with high performance due to their low resistivity, high hardness, melting point and elastic modulus. It was shown that the microstructure and mechanical properties of metal matrix composites were improved by adding TiB₂ particles [11]. Zhang discussed the dual role of TiB₂ particles in the Micro-arc oxidation process of the in-situ TiB₂/A201 composites [12]. Zhu studied the ablation resistance behaviors of the TiC-TiB₂/xCu ceramic-matrix composites [13]. Our team also carried out some studies on the arc erosion behavior of copper matrix composite [14–16]. After arc erosion, the quality loss of composites are reduced and the surface erosion pits are shallow by adding TiB₂ particles. With the increasing demand of high performance, how to further improve the arc erosion resistance of copper matrix composites is one of the concerns at present.

Some scholars added dual-scale reinforced particles into Fe-based, Al-based, Mg-based and ceramic-based composites. It was shown that the dual-scale reinforced particles greatly improved the hardness, strength, thermal conductivity and thermal stability of the composites due to the different strengthening effects and occupancy of multiple sized particles [17–19]. Lee presented a trans-

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Table 1: Properties of single-scale and dual-scale TiB₂/Cu composites

Particle size of TiB ₂ / μm	Relative density / %	Hardness / HBW	Electrical conductivity / % IACS
2	96.9	61.5	81.4
50	97.3	63.0	82.5
2+50(1:1)	98.0	66.8	84.7
2+50(1:2)	98.5	69.2	85.3
2+50(2:1)	97.6	65	84.3

parent electrode based on a dual-scale silver nanowire (AgNW) percolation network embedded in a flexible substrate to demonstrate a significant enhancement in the effective electrical area by filling the large percolative voids present in a long/thick AgNW network with short/thin AgNWs [20]. Zou reported a simple strategy for electrosynthesis of silicon carbide nanowires (SiC NWs)-derived carbon with dual-scale nanostructures for high performance supercapacitors [21]. The above research results provide a new idea for the design and development of high performance copper matrix composites. By multiple sized particle, the synergies between different particle sizes can be exerted. The comprehensive properties of copper matrix composites are expected to be further improved accordingly. At present, the fabrication of multiple sized particle reinforced copper matrix composites and their application are rarely reported.

In this paper, TiB₂/Cu composite with 5% volume fraction of single-scale and dual-scale TiB₂ particles were fabricated by powder metallurgy. Microstructure and comprehensive properties of TiB₂/Cu composites with single-scale and dual-scale reinforcements were discussed. The arc erosion behaviors of TiB₂/Cu composites were analyzed. The mechanism of arc erosion resistance of dual-scale TiB₂/Cu composites was proposed.

2 Material and methods

TiB₂ particles (5% vol.) were mixed with electrolytic copper powder. The average particle size of electrolytic copper powder was 75 μm and the purity was more than 99%. The average particle size of TiB₂ was 2 μm and 50 μm , respectively. The ratio of 2 μm over 50 μm TiB₂ particles were 1:0, 1:1, 1:2, 2:1 and 0:1. The fabrication process was as follows: TiB₂ particles were mixed with pure copper powder by ball milling. The milling time was 16 h and ratio of grinding media over material was 5:1. After ball milling, the mixed powder were subjected to a cold isostatic process with the pressure of 280 MPa for 20 min. The size of the compacted

samples were $\Phi = 50 \times 60$ mm. ZT-200-22Y sintering furnace was used for vacuum sintering. The sintering temperature was 950°C and the holding time was 90 min. After sintering, the sintered samples were further densified by hot extrusion. The extrusion temperature was 900°C and the extrusion ratio was 5:1.

Microstructure of the composites were observed with Axio Vert. A1 optical microscope. Hardness of the composite were tested by 320HBS-3000 digital display brinell durometer. The electrical conductivity of the composite were measured by Sigma 2008B1 digital conductivity meter. Thermal conductivity and thermal diffusion coefficient of samples at 25°C, 50°C, 100°C, 150°C, 200°C, 250°C and 280°C were measured by LFA447 laser thermal conductivity instrument.

The extruded composite was processed into $\Phi = 3.8$ mm $\times$ 10 mm cylindrical sample for arc erosion test by JF04C contact material testing system. Experimental parameters of arc erosion test are as follows: test voltage is 24V, currents are 5 A, 10 A, 15 A and 25 A, on-off frequency is 60 times per minute, contacts closed force is 0.4~0.6 N, number of test is 5000. Arc duration, arc energy and mass change of the samples were recorded. The arc erosion morphologies of the samples were observed by JSM-5610LV scanning electron microscope.

3 Result and discussion

3.1 Structure and properties of the TiB₂/Cu composites

Properties of single-scale and dual-scale TiB₂/Cu composites are shown in Table 1. Relative densities, hardness and electric conductivity of the dual-scale TiB₂/Cu composites are higher than the single-scale ones. When the ratio of 2 μm over 50 μm TiB₂ particles is 1:2, the density of the TiB₂/Cu composite is 98.5% and shows best properties. Its conductivity and hardness increase by 4.8% and 12.2% re-

Figure 1: Microstructure of single-scale and dual-scale TiB_2/Cu composites (a) $2\ \mu\text{m}$ single-scale TiB_2/Cu composite (b) $50\ \mu\text{m}$ single-scale TiB_2/Cu composite (c) $2\ \mu\text{m}+50\ \mu\text{m}(1:2)$ dual-scale TiB_2/Cu composite

Figure 2: (a) Thermal conductivity; (b) thermal diffusion coefficient; of single-scale and dual-scale TiB_2/Cu composites

spectively, compared with the composite reinforced by $2\ \mu\text{m}$ single-scale TiB_2 particles.

Relative density is an important factor affecting the properties of composite materials. According to Horsfield compact stacking theory, in the dual-scale TiB_2/Cu composites, large TiB_2 particles served as frame and small TiB_2 particles filled the gaps between large particles. The density of the dual-scale TiB_2/Cu composites increased accordingly. The different ratio of particle size led to different distribution and occupancy of reinforced particle. In the present work, the better ratio of $2\ \mu\text{m}$ over $50\ \mu\text{m}$ TiB_2 particles is 1:2.

Microstructure of single-scale and dual-scale TiB_2/Cu composites are shown in Figure 1. In $2\ \mu\text{m}$ single-scale TiB_2/Cu composites, the small TiB_2 particles are aggregated at grain boundaries (Figure 1(a)). When the composite is loaded, the aggregation of reinforcement at grain boundaries are crack sources and degrade the properties of composite [22]. In $50\ \mu\text{m}$ single-scale TiB_2/Cu composite, the interface between TiB_2 particles and matrix is poor, and gaps can be found around particles (Figure 1(b)). The

gaps may serve as crack sources under loading and jeopardize the properties of composite directly. In dual-scale TiB_2/Cu composite, neither aggregation nor gaps are observed since the ratio between large and small TiB_2 particles is moderate (Figure 1(c)). In ball milling process, the gaps after copper powder accumulation were filled with large TiB_2 particles and small TiB_2 particle successively. The density and properties of the composite increased consequently. As seen in Figure 1(c), large and small TiB_2 particles are evenly distributed in matrix. The large particles are surrounded by small particles without aggregation and gap.

Thermal conductivity and thermal diffusion coefficient of single-scale and dual-scale TiB_2/Cu composites are shown in Figure 2. Compared with the single-scale TiB_2/Cu composites (both $2\ \mu\text{m}$ and $50\ \mu\text{m}$), the thermal conductivity and thermal diffusion coefficient of dual-scale TiB_2/Cu composite with $2\ \mu\text{m}+50\ \mu\text{m}$ (1:2) TiB_2 are significantly improved. Dense microstructure without pore, as well as the uniform distribution of particles, contributed to the improvement of thermal properties.

Figure 3: (a) Arc duration; (b) arc energy; versus operation times of single-scale and dual-scale TiB_2/Cu composites at 24 V and 25 A

Figure 4: Mass changes of single-scale and dual-scale TiB_2/Cu composites after arc erosion test

3.2 Arc erosion behavior of the TiB_2/Cu composites

Arc duration/arc energy versus operation times of single-scale and dual-scale TiB_2/Cu composites at 24 V and 25 A are shown in Figure 3. Arc duration and arc energy increased as the number of operation times increased for both single-scale and dual-scale TiB_2/Cu composites. The arc duration and energy increase of 50 μm single-scale TiB_2/Cu composites were fast. When added 2 μm TiB_2 particles into the composite, the increase of arc duration and arc energy were significantly slowed. The high temperature produced by the arc caused the melting of composite surface. Small particles in copper matrix increased the viscosity of molten liquid, which suppressed the splashing of melted metal.

Mass changes of single-scale and dual-scale TiB_2/Cu composites after arc erosion test are shown in Figure 4. The mass of cathode decreased and the mass of anode increased after arc erosion. The mass transfer of single-scale TiB_2/Cu composites were significant, especially 50 μm single-scale TiB_2/Cu composite. The dual-scale TiB_2/Cu composite with 2 $\mu\text{m}+50 \mu\text{m}$ (1:2) TiB_2 shows lower mass transfer and loss. Dense microstructure and uniform particles distribution of the dual-scale TiB_2/Cu composite resulted in favorable mechanical and thermal property, which suppressed the mass loss under are erosion.

Arc erosion morphology of single-scale and dual-scale TiB_2/Cu composites after 5000 times arc erosion test are shown in Figure 5. The arc erosion morphologies of anode and cathode are quite different. The surface of anode was convex after arc erosion. Arc erosion pits formed at the surface of cathode, with globular particles of molten droplets scattered around the pits. According to the mass transfer measurement, a portion of the cathode material was transferred to the anode under the arc, and another portion caused material loss in the form of splashes.

The arc erosion of 50 μm single-scale TiB_2/Cu composite was severe, and the erosion area covers almost the entire field of view. The erosion area of 2 μm single-scale TiB_2/Cu composite was relatively small. Cremens [23] studied the relationship among particle spacing, particle size and particle content,

$$\lambda = \frac{2}{3d(\frac{1}{v} - 1)} \quad (1)$$

(λ : particle spacing, d : particle size, v : particle volume fraction). With the same content of TiB_2 particles, the larger the particle size is, the fewer the particles are in the copper matrix, and the distance between the particles is relatively larger. The large particle spacing resulted in copper enrich-

Figure 5: Arc erosion morphology of single-scale and dual-scale TiB_2/Cu composites after 5000 times arc erosion test (the erosion area of 50 μm single-scale TiB_2/Cu composite covers almost the entire field of view) (a) 2 μm , anode; (b) 50 μm , anode; (c) 2 μm +50 μm (1:2), anode (bulges on the anodes) (d) 2 μm , cathode; (e) 50 μm , cathode; (f) 2 μm +50 μm (1:2), cathode (erosion pits in the cathodes)

ment. Melting occurred in the copper enrichment firstly and then formed molten pools under arc. Then the copper liquid in the molten pool was splashed when the contact closed. A portion of the spray droplet formed a bulge in the anode. When the contact closed again, the anode bulge would first produce an arc. With the increase of contact times, the area of molten pool and spray increased, which resulted in a large arc erosion area.

Compared with single-scale TiB_2/Cu composites, the arc erosion of dual-scale TiB_2/Cu composite with 2 μm +50 μm (1:2) TiB_2 was slighter, characterized by smaller anode bulge area and cathode erosion pit. The density of dual-scale TiB_2/Cu composite with 2 μm +50 μm (1:2) TiB_2 was higher than the single-scale ones. The structure of single-scale TiB_2/Cu composites were relatively loose. Under the action of arc, the loose composite surface melted and absorbed a large amount of external gas. When the temperature dropped, the gases absorbed by the surface formed bubbles in the loose structure. In next arc erosion, these bubbles burst and splashed, and then formed a wide range of arc erosion morphology in anode and cathode.

Arc erosion microstructure of single-scale and dual-scale TiB_2/Cu composites at 25A are shown in Figure 6. Melting and gasification of contact materials were the main phase transition processes in arc erosion. With the increase of arc heat flow and temperature, molten metal flowed into contact surfaces. The arc force produced a splash of liquid, causing a large amount of material loss.

As shown in Figure 6, the heat generated by the arc caused the copper to melt and splash, then adhere to the surface of the sample after cooling and solidifying. The cathode melt was attached to the anode, resulting in a convex appearance of the anode. The surface of 2 μm single-scale TiB_2/Cu composite cathode melt was rough, as shown in Figure 6. This was because there were many small TiB_2 particles in the composite. When the high temperature of the arc melted the composite, these small TiB_2 particles increased the viscosity of the molten copper solution. After the molten droplets cooled, smaller spherical particles were formed.

In addition, liquid diffusion occurred on the cathode surface of the composites and metal pools were located near molten droplets, as shown in Figure 6(d), 6(e) and 6(f). In the process of contact between two poles, the melting temperature of the contact material was close to or higher than that of the copper matrix due to the arc. As the bipolar contacts continued to open, the molten bridge broke and arced. The high temperature of the arc melted the contact surface into a pool. Due to the low melting and boiling temperature of the copper matrix, when the two ends of the contact closed, the copper matrix would first melt and splash, resulting in material loss and transfer. As the temperature dropped, the material solidified to form a bulge at the anode and a ball and pool structure at the cathode.

In 50 μm single-scale TiB_2/Cu composite, large TiB_2 particles resulted in fewer particles and larger particle

Figure 6: Arc erosion microstructure of single-scale and dual-scale TiB_2/Cu composites at 25A (large molten droplets in Figure 6(a) and 6(d); large erosion area in Figure 6(e); flat erosion surface and small droplets in Figure 6(c) and 6(f)) (a) 2 μm , anode; (b) 50 μm , anode; (c) 2 $\mu\text{m}+50 \mu\text{m}$ (1:2), anode (d) 2 μm , cathode; (e) 50 μm , cathode; (f) 2 $\mu\text{m}+50 \mu\text{m}$ (1:2), cathode

spacing in the matrix. When the copper matrix was melted by the high temperature of arc, the molten pool area was larger, and the spherical molten material of cathode was large and the surface was smooth. The arc erosion of dual-scale TiB_2/Cu composite with 2 $\mu\text{m}+50 \mu\text{m}$ (1:2) TiB_2 was relatively slight. Compared with the single-scale TiB_2/Cu composites, the dual-scale TiB_2/Cu composites combined the supporting effect of large particles with the increasing viscosity effect of small particles. At the same time, the mixing effect of multiple sized particles overcame the large spacing caused by large particles, resulting in finer molten particles and shallow etch pit.

3.3 Mechanism of arc erosion resistance of dual-scale TiB_2/Cu composites

The arc erosion morphology of the TiB_2/Cu composites is closely related to plasma impact, thermal convection, Lorentz force and surface tension [24]. In the arc initiation phase, cations are rapidly bombarded the cathode pool due to the accelerating effect of electric field on cations. This rapid and massive plasma shock can cause flow in the central area of the cathode pool. In addition, Lorentz forces generated by electric current drive the solution to flow outward to both sides of the side wall of the molten pool. The cathode pool splashes during the collision of

anode and cathode. However, thermal convection causes molten metal to flow inward from the sides of the pool. And the surface tension of the molten metal will restrict the flow of the solution. Therefore, plasma impact and Lorentz force are the main factors causing the spatter, while thermal convection and surface tension are the main factors preventing the spatter. Compared with the cathode eroded by arc, the anode molten pool has the same four kinds of forces, but the anode is mainly bombarded by free electrons with lower mass. And its influence on the anode is much less than that on the cathode, so that the sputtering rarely happens. This is the main reason why the anode of TiB_2/Cu composite produces bulges while the cathode produces erosion pits and spray droplets under arc.

As seen in Figure 7, there are some defects in the contact surface of anode and cathode, such as cracks, pores, etc. The contact was on and off over and over again under the high temperature of arc erosion, which had a strong thermal impact on the surface of the material. Under the action of thermal stress, cracks formed by arc erosion materials usually expanded in multiple directions. When the cracks in these directions grew to cross each other, the physical properties of the contact surface of anode and cathode of the material would decline, and the arc erosion would be more serious. In this case, one of the potential causes of crack initiation and propagation was thermal tensile stress. The thermal conductivity and thermal

Figure 7: (a) Pores; (b) cracks; on the surface of TiB_2/Cu composites after arc erosion

Figure 8: Schematic of arc erosion behavior of dual-scale TiB_2/Cu composite

expansion coefficient of ceramic particles and copper matrix were different in the composites. As the material was heated or cooled, a thermal gradient was thus generated between the components. Therefore, under the high temperature of arc erosion, cracks would inevitably appear in ceramic particle reinforced copper matrix composites. The maximum temperature gradient of material without forming cracks (ΔT), namely thermal shock parameter of materials (R), is [25]

$$R = \Delta T = k\sigma C/E\alpha \quad (2)$$

(k : thermal conductivity, σ : material strength, E : Young modulus, α : coefficient of thermal expansion, C : constraint coefficient). According to equation (2), the generation of cracks in TiB_2/Cu composite during arc erosion was related to its thermal conductivity. The composites with good thermal conductivity had better thermal shock resistance. The thermal conductivity of the dual-scale TiB_2/Cu composite with $2\mu\text{m}+50\mu\text{m}$ (1:2) TiB_2 was higher than the single-scale ones. Therefore, the dual-scale TiB_2/Cu composite with $2\mu\text{m}+50\mu\text{m}$ (1:2) TiB_2 had better thermal shock resistance. In dual-scale TiB_2/Cu composite, the larger par-

ticles played a supporting role, while the smaller ones strengthened the matrix and increased the viscosity of the molten pool during arc erosion. Therefore, the effect of dual-scale TiB₂ particles effectively improved the arc erosion resistance of the composite. The schematic of arc erosion behavior of dual-scale TiB₂/Cu composite is shown in Figure 8.

Moreover, in the dual-scale TiB₂/Cu composite with 2 μm+50 μm (1:2) TiB₂, large TiB₂ particles appeared as particle fracture under loading, while small grain size particles deflected cracks. The large TiB₂ particle can inhibit crack initiation, while the small TiB₂ particle size can resist crack propagation. Therefore, in the arc erosion under the same conditions, it was more difficult for the dual-scale TiB₂/Cu composite with 2 μm+50 μm (1:2) TiB₂ to form cracks, which improved its arc erosion resistance.

4 Conclusion

1. For TiB₂/Cu composite with 5% volume fraction of single-scale and dual-scale TiB₂ particles, the dual-scale TiB₂/Cu composites have few structure defects, and TiB₂ particles with different size are uniformly distributed in the copper matrix. When the ratio of 2 μm over 50 μm TiB₂ particles is 1:2, the density of TiB₂/Cu composite is 98.5% and shows best mechanical and thermal properties.
2. In the process of arc erosion, the arc duration and energy of TiB₂/Cu composites increase with the increase of current. Compared with single-scale TiB₂/Cu composites, the arc erosion of the dual-scale TiB₂/Cu composite with 2 μm+50 μm (1:2) TiB₂ was slighter, characterized by smaller anode bulge area and cathode erosion pit.
3. On the one hand, dual-scale TiB₂ particles optimize the microstructure and thermal stability of the composite, which is conducive to alleviating arc erosion. On the other hand, the synergistic effect of different sized TiB₂ particles in the matrix improves the arc erosion resistance of TiB₂/Cu composite during arcing.

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