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Arc erosion behaviour of in-situ TiB₂/Cu composites with a three-dimensional network structure

Yihui Jiang, Le Han, Yingxin Xu, Fei Cao, Xiang Du, Fei Han, Lei Cai and Jialin Zhu
Shaanxi Province Key Laboratory for Electrical Materials and Infiltration Technology, Xi’an University of Technology, Xi’an, Shaanxi 710048, People’s Republic of China
E-mail: jiangyihui@xaut.edu.cn

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Abstract

Copper matrix composites (CMCs) with tailored heterogeneous structures at the mesoscopic scale are promising candidates for electrical contact materials. In this work, CMCs reinforced by an in situ formed three-dimensional network of TiB₂ particles were synthesized from Cu, Ti and B powder mixtures by reactive hot-pressing. The arc erosion behaviour of the fabricated CMCs was investigated by an electrical contact test. The distribution state of in situ TiB₂ depends on the particle size of the Cu powder. The critical size for forming a continuous network in 3 wt%TiB₂/Cu composites is estimated to be 24 μm. Once the continuous network is formed in CMCs, the arc energy and duration suddenly change to ultrasmall and stable values, and the erosion area and total mass loss after 5000 cycles of the contact test remarkably decrease. The results indicate that the CMCs reinforced by in situ networks of TiB₂ particles exhibit excellent arc erosion resistance.

1. Introduction

Since arc strike and friction problems are essential for contact materials applied in current-carrying condition in sliding electrical contact, the properties of resistance to arc erosion [1] and wear [2] have been paid much attention. Although the material surface can be protected from friction by forming a coating layer [2], this method will create a barrier to the flow of electrical current. Alternatively, without markedly damaging electrical conductivity, the arc erosion [3] and wear behaviours [4] of copper-based materials can be simultaneously enhanced by properly adding ceramic particles (e.g., Al₂O₃ [4, 5], TiB₂ [3, 6], SiC [7], and TiC [8]). Accordingly, copper matrix composites (CMCs) are potential candidates for electrical contact materials. Generally, it was considered that high machinal properties of CMCs could be achieved by uniformly dispersed ceramic reinforcement. For example, CMCs reinforced by dispersive TiB₂ or SiC particles exhibit high tensile strength [6] and wear resistance [7], respectively. However, the strengthening of homogenous CMCs is largely determined by increasing the reinforcement content, which can cause damage to the electrical conductivity [5–8]. The trade-off between strength and electrical conductivity limits their overall performance.

The design of metal matrix composites with tailored heterogeneous structures at the mesoscopic scale, as a promising candidate for operating conditions requiring excellent overall performance, has gradually received attention [9]. Among various artificially designed structures, composites with three-dimensional (3D) network structures exhibit both high strength and high conductivity, such as graphene-like network reinforced CMCs [10]. More significantly, it has been reported recently that carbon nanotube network-reinforced CMCs show superior arc erosion resistance [11], which is essential for electrical contact materials. However, ex situ introduced nanocarbon reinforcements often lead to weak interface bonding between the reinforcement and matrix. To optimize the effect of the 3D network structure, CMCs reinforced by an in situ formed 3D network of TiB₂ particles were fabricated in this work, and the arc erosion behaviour was investigated by an electrical contact test.

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2. Material and methods

Commercial Cu powder (purity of 99.9%), Ti powder (purity of 99.9%, particle size of 1 μm) and B powder (purity of 99.9%, particle size of 0.5 μm) were used to fabricate in situ 3 wt%TiB₂/Cu by reactive hot-pressing. Spherical Cu powders with different particle sizes (D_{Cu} = 1, 20, 40, 60, 80 and 100 μm) were selected. To retain the spherical morphology of Cu powders, the raw powders were blended in a vibrational blender for 3 h (ZrO₂ balls with diameters of Φ 6 mm, ball-to-powder weight ratio of 3:1, and frequency of 50 Hz were applied). Then, the mixtures were cold-compacted and hot-pressed. A stepped temperature-time program was applied in hot-pressing, i.e., a presintering stage (holding at 1193 K for 0.5 h with a pressure of 20 MPa) followed by a main sintering stage (holding at 1333 K for 1 h with a pressure of 25 MPa).

Arc erosion behaviour tests were carried out by an electrical contact tester (JF04C, Kunming Institute of Precious Metals). The cylindrical samples of Φ 4 × 10 mm were used. Each contact pair was tested for 5000 switching on-off operations with a voltage of 25 V DC, current of 10 A, contact force of 40 cN and electrode gap of 1 mm. Microstructures and phase compositions were investigated by scanning electron microscopy (SEM, JSE-6700F, JEOL) and x-ray diffraction analysis (XRD, Panalytical X'pert PRO), respectively.

3. Results and discussion

3.1. Formation of 3D network structure in CMCs

As shown in figure 1, after vibrational blending, the spherical morphology of Cu powder is mainly retained in the blended mixtures, and Ti and B particles are uniformly embedded onto the surface of Cu particles. During hot-pressing, TiB₂ particles are synthesized in situ at the original site of Ti and B particles. Accordingly, the 3D network of TiB₂ particles formed along the surface of the Cu powder. The thickness of the network will depend on the superficial area of Cu powder per unit volume for CMCs with a certain fraction of TiB₂. Theoretically, the finer the Cu powder is, the thinner the TiB₂ network will be. However, in practice, there is a minimum thickness due to the limitation of TiB₂ particle size. The average particle size of in situ formed TiB₂ in this work is approximately 1 μm.
which implies that a continuous network with one layer of TiB₂ particles should be at least 1 \( \mu \)m thick. Accordingly, there must be a critical size of Cu powder, \( D_c \), for forming a 3D continuous network of TiB₂ particles. Assuming that the Cu matrix is composed of equal-diameter spheres and the network has uniform thickness, the evolution of the theoretical thickness of the TiB₂ network with \( D_{Cu} \) in 3 wt%TiB₂/Cu can be calculated; see figure 2. \( D_c = 24 \mu m \) is obtained for the 1 \( \mu \)m thick TiB₂ network. For the case of \( D_{Cu} \geq D_c \), a 3D continuous network can be formed. In contrast, discontinuous TiB₂ particle clusters will be obtained when \( D_{Cu} < D_c \) occurs. As shown in figure 2, the distribution state of TiB₂ particles in \textit{in situ} fabricated CMCs is highly consistent with the theoretical prediction.

### 3.2. Arc erosion behaviour

The evolutions of arc energy and duration with switch on-off operation were measured for each CMC; see figure 3. For the case \( D_{Cu} \leq 20 \mu m \), there are violent fluctuations of arc energy and duration with operation cycle for both make-arc and break-arc. Once the 3D network is formed (i.e., \( D_{Cu} \geq 40 \mu m \)), stable arc energy and duration can be obtained, especially for the make-arc stage, and the arc energy and duration of 3D network CMCs are increased and then decreased with the increase of thickness of the TiB₂ network. Furthermore, abrupt

![Figure 2. Evolution of theoretical thickness of TiB₂ network in 3 wt%TiB₂/Cu composites with the particle size of Cu powder (lines) and inserted SEM micrographs of hot-pressed composites by using different Cu powders.](image)

![Figure 3. Fluctuation distribution curves and average values of arc energy (a)–(c) and arc duration (d)–(f) during the 5000 cycle contact test.](image)
changes in the average arc energy and duration of 5000 contact tests can be observed (see figures 3(c) and (f)). Compared with discontinuous CMCs, the values of 3D network CMCs decrease approximately 3 times in make-arc energy and 7 times in make-arc duration. It is worth to note that, both the arc energy and duration of 3D network TiB$_2$/Cu composites are about two orders of magnitude smaller than those of Ag-Ni contact materials \[12\].

Due to the significantly reduced arc energy and duration, the 3D network CMCs exhibit high arc erosion resistance. Consequently, the total mass change and erosion area after 5000 contact tests are remarkably decreased; see figures 4(a)–(c). The variation of total mass change with the thickness of the TiB$_2$ network is in accord with that of arc energy and duration for the case of 3D network CMCs, where the total mass change of $D_{\text{Cu}} = 40$ and $100$ $\mu$m sample is slightly increased because of oxidization. By comparing with CMCs reinforced with uniformly distributed TiB$_2$ \[3, 11\], the lower arc energy leads to less mass loss in the 3D network CMCs. Furthermore, the mass change trend of the anode is totally different between the discontinuous and 3D network CMCs. According to the typical anode eroded morphologies shown in figures 4(b) and (c), there are deep and large erosion pits on discontinuous CMCs ($D_{\text{Cu}} = 1$ $\mu$m), whereas an evident material accumulation region can be observed on 3D network CMCs ($D_{\text{Cu}} = 60$ $\mu$m).

The arc erosion behaviour of 3D network CMCs exhibits many features. Here, the above two most interesting features, i.e., make-arc energy/duration and anode mass changes, are discussed. Since the in situ formed TiB$_2$ particles can form protuberances on the contact surface, the arc is preferentially localized on TiB$_2$ tips during the make-arc stage. For the case of discontinuous CMCs, arc erosion concentrates on the arc starting point of TiB$_2$ clusters until this region melts, splashes or evaporates (figure 4(d)), which corresponds to a high arc energy and long arc duration. For the case of 3D network CMCs, the ignited arc can be dispersed by moving along the 3D continuous network (figure 4(e)), which results in rapid arc extinguishing. Therefore, the arc energy and duration decrease greatly when the 3D continuous network is formed. Furthermore, during arc concentrated erosion for discontinuous CMCs, the short arc is assumed to be the dominant aspect of the steady arc burning stage. However, the dispersing arc can develop into a long arc by moving along the 3D continuous network. The variation in the distribution state of TiB$_2$ particles causes the transformation from metallic arcs (short arcs) to gaseous arcs (long arcs). The metallic arc corresponds to material transfer from the anode to the

![Figure 4. Mass change (a), anode 3D morphologies (b), (c) and anode SEM images (d), (e) of in situ fabricated CMCs after 5000 cycles of contact test.](image-url)
cathode [13]. Meanwhile, arc concentration erosion causes severe splashing and evaporation on the contact surface of the cathode. These two factors result in mass loss in both the anode and cathode for discontinuous CMCs. However, the gaseous arc leads to material transfer from the cathode to the anode [13], and the anode mass increment of 3D network CMCs is observed after electrical contact tests.

4. Conclusions

(1) By uniformly embedding Ti and B particles onto the surface of Cu particles, the TiB2 particles can be formed along the surface of the Cu powder by reactive hot-pressing. To form a continuous network in 3 wt% TiB2/Cu composites, the critical size of Cu powder was estimated to be 24 μm.

(2) As ignited arc can be dispersed by moving along the 3D network, the arc energy and duration of TiB2/Cu composites decrease greatly by changing the distribution of TiB2 particles from discontinuous particle clusters to 3D network.

(3) By forming a 3D network, a change in the arc burning state (from metallic arc to gaseous arc) leads to the variation in mass transfer behaviour between the anode and cathode. The 3D network CMCs exhibit small arc erosion areas and total mass loss, which correspond to high arc erosion resistance.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

ORCID iDs

Yihui Jiang © https://orcid.org/0000-0003-4003-9420
Fei Cao © https://orcid.org/0000-0002-6387-0658

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