Intuitive Analysis of the Microtribological Behavior of Copper-Coated Graphite–Graphite/Cu Composites with High Graphite Contents

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ABSTRACT: To improve the combination of graphite and copper, the friction and wear of a graphite/copper composite with a high content of graphite (50 wt %), copper-coated graphite were used to modify it. To observe the distribution law of each phase in the material and the change of composite surface structure after the friction and wear experiment, scanning electron microscopy (SEM) and transmission electron microscopy (TEM) were used to characterize the microstructure, friction film, debris, and friction cross section of the composites. The results show that the large particle size of copper-coated graphite is anisotropic in the material, which helps to form a friction film with a high graphite content on the contact surface. TEM images of the friction film and debris directly reflect the structure changes of graphite and copper during friction; under normal load and shear force, interlamellar detachment and interlamellar fracture of graphite occur, and its edge is folded and crimped, resulting in the loss of an ordered state in some regions, which results in the instability of crystal lattice and the transition from an ordered to disordered state of graphite, resulting in the (002) halo ring in FFT results. Severe plastic deformation and oxidation reactions occur in copper, and copper oxides are formed, forming a high-strength and smooth oxide film in the metal-rich area and improving the wear resistance of the material. TEM images of the friction section directly show that an inverted triangular deformation zone is formed on the surface of the sample after friction and wear experiments. The edge of the deformation zone is stepped, consisting of a drag zone and an accumulation zone, and the surface of the contact zone is covered by a carbon film.

1. INTRODUCTION

The graphite/Cu (G/Cu) composite material has the self-lubricating property of graphite and the excellent thermal and electrical properties of copper, therefore, it is widely used in the preparation of lubricating materials and sliding electric contact materials such as commutators, brushes, and pantograph carbon skateboards. As an important application field that utilizes graphite/copper composites, electric contact materials need to have excellent electrical conductivity, wear resistance, and low friction coefficient. With the rapid development of transportation, electric power, and electronics industries, the service environment of electrical contact materials is more demanding, requiring them to have better mechanical properties and friction and wear properties. Because graphite and copper are only connected by physical engagement, there are many structural defects in the material, and it is difficult to meet all the above performance requirements at the same time.

To improve the combination of graphite and copper and improve the properties of composites, modification methods are often used. One method is to add alloying elements that are prone to form carbides, but segregation is easy to occur at the interface, resulting in poor mechanical properties of the materials. The addition of new carbon material reinforcing agents and the modification of the graphite surface have been performed. Many scholars have improved the mechanical properties and friction properties of composites through the addition of appropriate new high-performance materials such as carbon nanotubes (CNTs), carbon fibers (CFs), and graphene. However, nanomaterials are prone to agglomeration due to their high surface activities. To develop their mechanical properties, the composites prepared have a high copper content, which leads to poor friction and wear performance of the composite material, large wear of the grinding material, a complex preparation process, and high...
preparation costs, limiting the amount of applications of composites. Surface modification of graphite such as metal plating is an effective way to improve the combination of graphite and copper.

Metal coating on the surface of carbon material is a feasible method for improving the bonding strength.\textsuperscript{17} Numerous studies show that copper, nickel,\textsuperscript{15} and silver coatings on the surface of carbon materials can improve the bonding strength between strengthened graphite and metal phases. The process of electroless copper plating on the graphite surface is mature, the preparation cost is low, and the surface metal coating effect is good. When it is used to modify graphite/copper composites, it is helpful to form a complete metal network structure in the material, and high graphite content composites with good electrical conductivity and wear resistance can be prepared by the conventional powder metallurgy method, which has good economic benefit. In recent years, there have been many studies on the combination of copper-coated modified graphite and copper on the surface of graphite, but there are few studies on the friction and wear properties of copper-coated graphite modified graphite with a high graphite content. Wang et al.\textsuperscript{19} coated tungsten–copper (W–Cu) on the graphite and fabricated GF (W–Cu) composites by vacuum hot-pressing sintering. The tensile strength achieves values of 91.9 ± 2.6 MPa, more than twice as high as GF/Cu composites. The ultrahigh in-plane TC and lowest through-the-plane CTE can reach 929.8 ± 5.0 W m\(^{-1}\) K\(^{-1}\) and 6.3 ± 0.2 ppm K\(^{-1}\), respectively, and the better thermal response rate can be 0.67 °C s\(^{-1}\). Cheng et al.\textsuperscript{17} coated nickel–iron alloy and copper on graphite by electroless plating and fabricated composites by SPS sintering. The results show that the mechanical properties and wear resistance of graphite composites are improved greatly after surface modification, and the wear rate of the composites is about one-quarter of that of the graphite/copper composites.

Most studies on friction and wear properties of C/Cu composites and reinforcement materials in different conditions are carried out from a macro perspective,\textsuperscript{17,20} such as observing the friction coefficient, the wear rate, and scanning electron microscopy (SEM) diagrams.\textsuperscript{21} However, few studies have observed the morphology, structure, and crystal changes before and after friction experiments from a microscopic perspective.

With respect to the issues above, G/Cu composites with different contents of copper-coated graphite–graphite were produced through the powder metallurgical method, and the effects of copper-coated graphite on the tribology behavior of the samples after ring-block friction and wear experiments were researched. To observe the distribution of copper-coated graphite in the composite and the transformation of the morphology, structure, and composition of each phase on the material surface before and after friction and wear experiments, fine characterization instruments such as SEM and TEM were selected to characterize the surface, worn surface, debris, and friction cross section. The physical and chemical reactions of the main components in the process of friction can be expressed through the changes of morphology, structure, and crystal phase. This work provides more direct evidence for studying the reinforcing mechanism of copper-coated graphite and the friction mechanism of composites.

2. MATERIALS AND EXPERIMENTS

2.1. Materials. The grain diameters of electrolytic copper powders and graphite used during the study are about 50 and 150 µm, respectively. The physical parameters of copper-coated graphite are listed in Table 1.

| Raw material | Grain size (µm) | Coating thickness (µm) | Coating content (mass fraction, %) | Coating way |
|--------------|----------------|------------------------|-----------------------------------|-------------|
| Copper-coated graphite | 100–150 | 0.5 | 50–55 | Electroless plating |

2.2. Preparation of the Samples. The experimental scheme was set by ensuring that the graphite mass ratio was 50% and increasing the copper-plated graphite content from 10 to 50 wt % with a gradient of 10 wt %. According to the set proportion, the electrolytic copper powder, graphite powder, and copper-plated graphite powder were weighed and fully mixed, and then samples were prepared by the powder metallurgy method. During the preparation process, the samples were pressed for 30 s under a pressure of 300 MPa and then sintered under 780 °C for 2 h under the environment of NH\(_3\). After cooling to room temperature in the sintering furnace, the samples are obtained.

2.3. Test Procedures. An MM-2000 ring-block friction testing machine was used to perform tests of the G/Cu and copper-coated graphite-G/Cu composites. To make the results more accurate, the sample surface was polished with an 800 mesh sandpaper. The friction and wear experiments were carried out for 300 min under 30 N load and 0.42 m/s sliding velocity, and a pure copper ring with an outer diameter of 40 mm and inner diameter of 20 mm was used as friction pairs in the experimental process. The wear rate was calculated by formulas 1 and 2:

\[
W = \frac{10}{R^2 \arcsin \frac{b}{2R} - \frac{b}{2} \sqrt{R^2 - \left(\frac{b}{2}\right)^2}}
\]

(1)

\[
\omega = \frac{W}{F \times L}
\]

(2)

where \(R\) is the external radius of the copper ring, \(b\) is the width of the grinding mark after the friction wear test, \(F\) is the friction load, and \(L\) is the sliding distance.

A Tecnai F20 TEM instrument was used to characterize the microstructure and morphologies of the debris, friction film, and friction cross section of the composites. And the debris was dispersed by ultrasonic treatment in alcohol for half an hour. Friction film samples were prepared by the following methods: a 5% (mass fraction) PVA solution was first dropped on the friction surface and then solidified for 24 h at room temperature to form the PVA film. After careful tearing of the dried PVA film, PVA was dissolved in a 90 °C water bath, and the friction film was collected with a micro-grate for observation and analysis after drying. A Helios Nanolab 600i double-beam electron microscope was used to cut the friction section with a thickness of 30–35 nm along the friction direction of the samples after the friction wear test by a focused ion beam (FIB). After selecting the cutting area on the friction surface, the long strip Pt was plated on its surface, and then thin slices were obtained after hollowing out both sides and were finely thinned. After the slices were thinned to 30–35 nm, the sample was obtained.
3. RESULTS AND DISCUSSION

3.1. Micromorphologies of Composites. The distribution patterns and copper-coated graphite directions in the materials can be observed more intuitively through the SEM diagrams of the copper-coated graphite-G/Cu composites; to observe the distribution of copper-plated graphite in the material, the surfaces with vertical (Figure 1a,c,e) and parallel (Figure 1b,d,f) pressing directions were characterized, respectively. For comparison, the microstructure and morphologies of the composites with copper-coated graphite—graphite contents in the range of 0—50 wt % are shown in Figure 1. The images show that the distribution direction of copper-coated graphite is perpendicular to the pressing direction due to its large particle size, and the copper coating increases the copper-coated graphite density. This reduces the agglomeration of the graphite phase and the copper phase due to the large density difference. In addition, a continuous interface is formed between graphite and copper, and there is no obvious gap on the interface. The continuous interface forms a network structure, and a three-dimensional network copper structure is formed in the composite. With the increase of the copper-plated graphite, the copper network structure becomes more and more complete. The coating tightly binds to graphite, improving the interface bonding, which is consistent with the study of Liu et al.\textsuperscript{22} and Wang et al.\textsuperscript{23}

3.2. Friction Coefficient and Wear Rate. After friction and wear experiments, the friction coefficient and wear rate of the copper-coated graphite-G/Cu composites with copper-coated graphite contents from 0 to 50 wt % are shown in Figure 2. The friction coefficients and wear rates of the two kinds of materials show that the copper-coated graphite content greatly affects the tribological properties of the composites. When the content of copper-plated graphite increases from 10 to 50%, the friction coefficient decreases from 0.203 to 0.16. The content of copper-plated graphite on the surface of the material increases with the increase of its content, which is conducive to the formation of a high graphite content friction film on the surface of the material and reduction of the friction coefficient of the composites.

3.3. Microtribological Behavior. 3.3.1. Visual Analysis of the Worn Surfaces and Debris. Figure 3 shows the SEM images and energy-dispersive spectroscopy (EDS) patterns of the worn surfaces and debris of the copper-coated graphite-G/Cu composites with copper-coated graphite contents of 0 (Figure 3a,c), 20 wt % (Figure 3b,d), and 40 wt % (Figure 3c,f).

Compared to the composites without copper-coated graphite, the 20 wt % copper-coated graphite-G/Cu composites have friction films with fewer cracks and pits, but abundant grooves are formed along the friction direction on the worn surface. There are almost no abrasive chips with large particle sizes on the worn surface, and the total number of abrasive chips is much less than that of the other two kinds of composites. The low hardness leads to hard microbumps that scratch the sample under shear action and leave scratches on the surface, so abrasive wear is more likely to occur on the friction surface in the initial friction process. This scratching leads to abundant grooves produced on the friction surface, although there are few surface cracks and large holes caused by adhesive wear and fatigue wear. The SEM image also shows that the friction film is thin and has a good binding effect with the matrix, confirming that it can effectively maintain the integrity and inhibit the renewal rate of the friction film. This film exhibits a lower coefficient of friction and the lowest wear rate of the 20 wt % copper-coated graphite-G/Cu composites. When the content of the copper-coated graphite increases to 40 wt %, the SEM images and EDS patterns of the worn surface (Figure 3c)
and debris (Figure 3f) show that the friction films formed on the contact surfaces are thick and completely cover the surfaces of the composites. There were fewer furrows on the worn surface, but there were large amounts of fine grindings and cracks along the sliding directions. The cracks cause the area around it to warp away from the friction surface, the combined action between the matrix is very weak, and the friction layer near the crack easily breaks off. Because of the long crack, the debris particle size is large, which leads to large increases in the wear rates of the composites; the results are similar to those of Liu et al.\textsuperscript{24} The binding effect between the copper-coated graphite on the surface, copper oxide, and lamellar graphite transferred to the surface is very low, which accelerates the renewal of the friction layer under the action of friction and further increases the wear rates of the composites.

To further verify the above conclusions, a Tecnai G2 F20-type TEM instrument was used to characterize the crystal structures, microstructures, and micromorphologies of the debris.

**Figure 4.** (a) TEM micrograms and (b–d) HRTEM micrograms and FFT images of debris of G/Cu composites.
Figures 4 and 5 show the microstructures and morphologies of the debris of the G/Cu composites and 20 wt % copper-coated graphite-G/Cu composites, respectively. The TEM microgram shows that the debris has various forms, some of which are caused by interlayer shedding of the surface graphite under shear force action or rolling the accumulated fine chips under furrow cutting action, while other large debris particles fall off under the action of fatigue wear. The exfoliated lamellar graphite is relatively neat, and its surface is flat without evident folding. The corresponding high-resolution TEM (HRTEM) image implies that its structure and components are pure graphite, and due to the continuous cyclic stress, the graphite expanded and the spacing of the layers widened. The composition of the ground chips is not uniform, the edge of the ground chips is relatively smooth and irregular, and the ground chips are roughly elliptic. The composition here is relatively complex, where graphite, copper, and copper oxide coexist. The corresponding HRTEM images (Figure 4c,d) display a large number of structural deformation areas and structural defects, and the direction and degree of deformation are different. Most of the deformation areas exist near the grain boundary, indicating that the debris comprises various components of finely ground chips that have simply piled up. The metal-rich area in the process of friction at the same time physical and chemical changes, plastic deformation and flow under the action of normal load after the formation of deformation zone, oxidized copper oxide formation oxide film. Copper is easily oxidized by oxygen and water vapor to form an oxide film. The oxide film is beneficial to increase the strength of the friction film but destroys its integrity, so it is easy to initiate cracks at the grain boundary, expand along the friction direction, and finally fall off. The results of fast Fourier transform (FFT) also show that there are many kinds of structural crystals in this region; CuO and Cu$_2$O with different crystal planes are interpressed and interpenetrated. Oxidative wear mainly occurs when there is exposed copper on the surfaces of the sample and friction pair. Once a relatively complete friction film is formed on the surface, the possibility of oxidation wear is reduced.

For 20 wt % copper-coated graphite-G/Cu composites (Figure 5), HRTEM images of two kinds of abrasive chips with different morphologies reveal different compositions and crystal structures. The HRTEM and FFT images (Figure 5b) of lamellar graphite show that the graphite on the surface of the grinding chip deforms seriously after the continuous action of stress, the graphite layer spacing widens, and different degrees of distortion and breakage occur, even leading to interlaminar fracturing. The graphite surface is covered with a layer of metal oxides and combined with graphite is relatively close. This is due to the copper coating on the surface of graphite, which expands the area of copper on the surface of composites and spreads to the surface of graphite after oxidation deformation, forming a thin metal oxide film, which enhances the surface strength and improves the bonding strength with graphite.

The HRTEM and FFT images of the accumulated debris in Figure 5c,d show that the contents of copper oxides here are relatively high, there is no apparent evidence of graphite, and there are many deformation areas at the edge of the debris. Deformation areas with different sizes and deformation directions are attached to each other, and grain boundaries with different spacings are formed. The degree of deformation determines the state of the boundary connection, and a wide crack is formed between the two phases when the crystal
orientation of adjacent regions is different and the deformation degree is deep. Moreover, the two adjacent different phases are easy to separate under the action of cyclic stress because cracks develop on the friction surface, which damage the surface friction layer.

3.3.2. Intuitive Analysis of the Friction Film. The selected area electron diffraction (SAED) spectra (Figure 6a) show the crystal plane information of the diffracted crystal from friction. The presence of copper oxide directly shows the occurrence of oxidation wear. When the contact surface temperature rises under the action of friction heat, copper is easily oxidized into CuO, Cu₂O, and CuCO₃. The high graphite content in the samples results in complete and thick friction films on the contact surfaces. The morphological images of the G/Cu composites (Figure 6b) and the 20 wt % copper-coated graphite-G/Cu composites (Figure 6e) show that the friction films made through the stacking and pressing of finely ground chips are relatively complete. The friction films for the G/Cu composites are formed upon layer-by-layer accumulation of finely ground chips with different shapes and sizes. The shapes of the finely ground chips in this area are relatively regular, and most of them are elliptic lamellae with a large particle size range and smooth edges. Based on the above analysis, it is speculated that most of these chips are composed of copper and its oxide. Some sharp and neat long-strip chips, which are narrow and short, can also be observed on the surface. Such chips may be formed by interlayer shedding of small-particle-size graphite or by cutting the surface carbon film for abrasive wear. The HRTEM images of the debris edges show that the graphite content is relatively high there, the graphite crystal structure is destroyed under the actions of stress and shear force, and some of the structures turn into disordered structured carbon. Because of the poor bonding strengths between the graphite phase and copper oxides in debris, cracks are more likely to occur there under cyclic stress action. Figure 6f–i shows that a large number of deformation areas with different degrees and directions exist in the copper phase-enrichment area, and the enlarged view of the deformation area shows that there are wide boundary gaps at the edge. As the experiment proceeded, the cracks were created and extended under stress, causing local shedding of the friction layer. Due to the structural defects of the samples and the low strength of the friction layer, it is easy to go through the process of generation, enrichment, shedding, and regeneration of the friction film in this area.

In contrast, the composites with 20 wt % copper-coated graphite exhibit better friction and wear performance, and their friction coefficients and wear rates are lower than those of the G/Cu composites. The friction film of it has a higher graphite content and better integrity, and the friction coefficients of it

Figure 6. (a) SAED spectra, (b) TEM microgram of the G/Cu composites, (c, d) HRTEM micrograms of the frame in (b), (e) 20 wt % copper-coated graphite-G/Cu composites, (f) enlarged microgram of \( \Box \) area in (e), (g) enlarged microgram of \( \bigotimes \) area in (e), and (h, i) enlarged microgram of \( \bigcirc \) area in (e).
are effectively reduced. The composites containing 20% copper-plated graphite have better mechanical properties, the oxide film formed in the metal-rich area enhances the strength of the friction film, and the thickness of the friction film formed is moderate, which effectively reduces the wear rate of the composite.

3.3.3. Intuitive Analysis of the Friction Cross Section. For the copper-coated graphite-G/Cu composites, the SAED spectra, TEM, HRTEM micrograms, and FFT images of the friction cross section show that because of the special contact mode of ring-block friction and wear, the friction cross section exhibits different deformation strengths and crystal structures. The TEM micrograms (Figure 7a) show that the deformation area presents a triangular trend, where the deepest deformation can reach 2–3 μm. The length of the deformation zone, crystal structure, and composition on each side of the center position are different due to the different force directions and magnitudes. Along the direction of friction, the deformation is divided into the accumulation zone and the drag zone, where the lowest point is the center. In the friction direction, because of the serious accumulation of ground debris, the deformation zone is small, the degree of deformation is deep, and the crystal structure at the edge of the deformation area is more complex. To further study the structural differences in each region, the friction film (Figure 7b), dragging area (Figure 7c), and
The structure is damaged to a large degree, and independent graphite appears to be pulled out from the matrix, graphite is high and the distribution of graphite is directional. Close to the friction film area, the content of graphite is high and the distribution of graphite is directional. The whole graphite appears to be pulled out from the matrix, the structure is damaged to a large degree, and independent massive metal oxides formed by copper oxidation appear. At the stress concentration point, the bonding effect between copper and other surrounding phases is destroyed, forming a wide space that causes the surface carbon film to be prone to falling off. Figure 7c,d shows that there are abundant metal oxide rich areas with many deformations there, and the grains between the graphite phase and metal phase are evident. The graphite content is high in the boundary area, and the structure has been seriously damaged under the external force. The interlaminar strength of graphite decreases, and interlaminar shedding occurs. The splitting of the copper oxide breaks the graphite, forms graphite fragments, and even breaks the fragments into amorphous carbon structures. The images of FFT of the HRTEM in different areas show that the composition of grains in the two regions is similar, mainly copper oxide and graphite, but the phase distribution and crystal plane orientation of grains are different. Most of the deformation areas are mixed extrusion of CuO and Cu2O. The SAED spectra further confirm the above view. Figure 7e shows the different crystal planes of CuO, graphite, and chaoite. The deformation products of graphite participate in the diffraction, which intuitively reflects the occurrence of chemical and physical reactions in the friction process.

3.3.4. Analysis of the Friction Mechanism. Understanding of the friction mechanism of composite materials can be utilized to take effective corresponding measures for improving the friction and wear properties, reducing the amount of wear, and increasing the service life of composites. Based on the above information, the friction mechanism of the composites in the friction process is analyzed, as shown in Figure 8.

At the initial stage of friction, the contact area between the composites and the anti-grinding material is small, and there is only a thin film because of physical adsorption on the contact surface. Under the action of external force, the contact microbump easily destroys the physical adsorption film and enters the contact surface, forming furrows on the surface under the action of friction. Frictional heat is easily generated in the friction process, increasing the temperature of the contact surface. When the temperature increases, the exposed copper phase is prone to oxidation by oxygen in the air, thus forming an oxide film on the contact surface. An oxide film with a complete morphology is helpful for reducing the friction coefficient of the composites. Moreover, the exposed copper phase is softened, adhesive wear occurs as the surface temperature rises, and point pits tend to form on the surface. As the experiment continues, the copper phase on the surface becomes covered by an oxide film and fine debris, reducing the probability of oxidation wear and adhesive wear. Meanwhile, according to the results of Nogueira et al., the graphite phase deforms under the action of cyclic stress and finally falls off to form lamellar graphite, and helped to form a friction film with a high graphite content. At the later stage of the friction experiment, the contact surface area increases, and a complete friction film is gradually formed, making the surface flatter. The copper phase barely exhibits direct contact, reducing the oxidation wear and adhesive wear. The area around the hard microconvex points is filled with fine debris, which increases the contact area and reduces the abrasive wear, mainly dominated by fatigue wear. After deformation and the accumulation of debris on the surface, a constant changing friction layer is formed, and its thickness and renewal speed are related to the wear rate of the composite material.

4. CONCLUSIONS

The following conclusions are obtained:

1. Adding the appropriate amount of copper-coated graphite can effectively reduce the friction coefficient and wear rate of composites. As characterized by SEM and TEM, the composition, morphology, and crystal structure of the surface of the deformation zone show that the graphite phase parallel to the friction direction is the lower layer under the cyclic stress, and finally, the interlayer shedding occurs and then the carbon film forms on the friction surface, which effectively reduces the friction coefficient of the composite. Oxidation and plastic deformation occur in the copper phase, and a large amount of deformation zones appears in the friction layer.

2. The TEM, HRTEM, and FFT images of the friction cross section show that the deformation zone with stepped edges is mainly composed of an accumulation zone, a drag zone, and a carbon film. The carbon film plays a self-lubricating role and reduces the friction coefficient. The components here are seriously deformed, and a rich area of metal oxide and carbon material is formed. The metal oxide enrichment area is mainly formed by the extrusion and penetration of CuO and Cu2O, forming a large number of small deformation areas.

3. The initial stage of the experiments is mainly dominated by abrasive wear and adhesive wear under the action of furrowing and frictional heat. As the exposed copper is oxidized by oxygen in the air, oxidative wear occurs and an incomplete oxide film is formed on the surface of the copper-rich area. The later stage of the experiment is mainly dominated by fatigue wear, and a complete friction film has been formed.

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■ REFERENCES

(1) Chuan Jun, T.; Chen, D.; Chen, Z. H.; Xia, J. T. Improving the Tribological Behavior of Graphite/Cu Matrix Self-Lubricating Composite Contact Strip by Electroplating Zn on Graphite. Tribol. Lett. 2008, 31, 91–98.

(2) Moustafa, S. F.; El-Badry, S. A.; Sanad, A. M.; Kieback, B. Friction and wear of copper–graphite composites made with Cu-coated and uncoated graphite powder. Wear 2002, 253, 699–710.

(3) Sun, Q.; Wang, Z.; Yin, B.; Yang, J.; Liu, J.; Liu, Y.; Cheng, J.; Zhu, S.; Qiao, Z. The tribological properties and wear mechanism of copper coated graphite doped SiAlon ceramic composites at wide range temperature from 25 to 800 °C. Tribology International 2018, 123, 10–16.

(4) Cui, G.; Niu, M.; Zhu, S.; Yang, J.; Bi, Q. Dry-Sliding Tribological Properties of Bronze–Graphite Composites. Tribol. Lett. 2012, 48, 111–122.

(5) Grzonka, J.; Kruszewski, M. J.; Rosiński, M.; Ciupiński, L.; Michalski, A.; Kurszydłowski, K. J. Interfacial microstructure of copper/diamond composites fabricated via a powder metallurgical route. Mater. Charact. 2015, 99, 188–194.

(6) Zhimeng, T.; Wang, Z.; Xu, L.; Libo, Z.; Zhaohui, H.; Jianghua, L. Thermal and tribological properties of MoS2 doped graphite/copper composites by microwave sintering. J. Mater. Res. Technol. 2021, 15, 6001–6010.

(7) Kovicik, J.; Emmer, Š.; Bielek, J. Thermal conductivity of Cu-graphite composites. Int. J. Therm. Sci. 2015, 90, 298–302.

(8) Grandin, M.; Wildlund, U. Friction, wear and tribofilm formation on electrical contact materials in reciprocating sliding against silver-graphite. Wear 2013, 302, 1481–1491.

(9) Zhu, L.; Mazhong, Y.; Wang, L.; Shengan, C. Effects of foam copper on the mechanical properties and tribological properties of graphite/copper composites. Tribol. Int. 2020, 148, No. 106164.

(10) Zhang, P.; Lin, Z.; Wei, D.; Wu, P.; Cao, J.; Shijia, C.; Qu, X. A high-performance copper-based brake pad for high-speed railway trains and its surface substance evolution and wear mechanism at high temperature. Wear 2020, 444-445, No. 203182.

(11) Ran, L.; Peng, K.; Yi, M.; Lin, Y. Ablation property of a C/C-Cu composite prepared by pressureless infiltration. Mater. Lett. 2011, 65, 2076–2078.

(12) Zhu, J. M.; Li, J. W.; Liu, T.; Chen, Z.; Fang, H. C.; Xiao, P.; Kong, F. Differences in mechanical behaviors and characteristics between natural graphite/copper composites and carbon-coated graphite/copper composites. Mater. Charact. 2020, 162, No. 110195.

(13) Guo, L.; Gang, K.; Xhaqian, L.; Jie, T.; Jian, P. Microstructure and flexural properties of C/C-Cu composites strengthened with in-situ grown carbon nanotubes. J. Alloys Compd. 2017, 694, 1054–1060.

(14) Bashir, B.; Shaheen, W.; Asghar, M.; Warsi, M. F.; Khan, M. A.; Haider, S.; Shakir, I.; Shahid, M. Copper doped manganese ferrites nanoparticles anchored on graphene nano-sheets for high performance energy storage applications. J. Alloys Compd. 2017, 695, 881–887.