Effect of flake graphite content on wear between behavior between P/M copper-based pantograph slide and contact wire

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Abstract
In this work, chromium-containing copper matrix composites with different flake graphite content (1.8 wt%, 2 wt%, 2.5 wt%) were fabricated by inexpensive powder metallurgy method, and the mechanical properties, friction properties and microstructure of graphite/copper matrix composites were studied. Friction experiments were conducted with copper-based composite materials and copper rings to examine the effect of graphite on the wear of the bow-net structure. During mechanical wear, the wear rate of the copper ring corresponding to the sample increased with the increase of the graphite content in the sample, while the wear rate of the copper ring corresponding to the 1.8 wt% sample was the smallest. In the current-carrying wear process, the wear rate of the 2 wt% sample corresponding to the copper ring is the lowest. Through elemental analysis, it was found that material transfer occurred on the worn surface during wear. In the process of mechanical wear without current-carrying wear is caused primarily by adhesion, abrasion, and oxidation. In the process of current-carrying wear, wear is mainly caused by adhesion, electrical, and oxidative abrasion.

1. Introduction
Copper-based powder metallurgy (P/M) materials have good conductive and thermal conductivity and corrosion resistance and are widely used in electronics, electric power, machinery, chemical industry, and other fields. The comprehensive performance serves as an ideal material for the preparation of modern self-lubricating friction parts and sliding electrical contact parts. It plays an important role in the harsh working environment, such as electrical switch contact, brush, and electric locomotive pantograph slide plate [1–5]. However, the copper-matrix composite material without graphite does not have excellent anti-friction properties and cannot meet the requirements for the use of pantograph skateboards. In order to improve the performance of self-lubricating materials, the researchers tried different kinds of lubricants, such as graphite materials [6, 7], MoS2 [8], and WS2 [9]. Among them, copper-based graphite composite materials are the most widely used self-lubricating materials. However, due to the hardly wetting between copper and graphite at high temperatures, the interface bonding effect between the copper matrix and the lubricating component (graphite) is unfortunate during high-temperature sintering restricts the performance of the copper-based graphite composite material [10–13]. To cope with this problem, it is usually strengthened by adding an alloying element such as nickel or iron to improve the mechanical strength of the composite material [14, 15]. Besides, Zn can also be used as a modified material for graphite in a graphite/Cu-based composite material. That is, zinc-coated graphite powder is used instead of graphite powder. The electroplated zinc layer can significantly improve the sintering process of the composite material, reduce the porosity, and improve the wear resistance and friction reduction [16].

The pantograph slide is an important collector component in the locomotive power supply system. Through the contact between the pantograph and the transmission line, the current on the transmission network is guided and transmitted to the locomotive power supply system to maintain the normal operation of the electric locomotive. The pantograph skateboard and the catenary wire form a pair of mechanically and electrically...
coupled pairs of special friction pairs. Once the skateboard on the high-speed electric locomotive fails, it will seriously endanger the driving safety. Therefore, it is required to be economical and safe to use. It has little wear on the contact net wire and has sufficient service life without affecting the relationship between the bow and the net [17]. In order to obtain a copper composite pantograph material with high lubricity, the graphite content can be increased. The high content of graphite can significantly improve the lubricity of the composite material and reduce the mechanical properties of the composite material. Therefore, the composite material lubricity and excellent mechanical properties coexistence still have plagued researchers. Enze Xu et al. studied graphite cluster/copper-based powder metallurgy composite. Ordinary graphite particles were replaced with large graphite clusters to reduce the graphite/metal interface, thereby improving the sintering performance and improving the mechanical properties. In this work, a series of new copper-based pantograph sliding materials with high flake graphite content were designed. The effects of different flake graphite contents on the mechanical properties and friction properties of graphite/copper matrix composites were studied. The effects of different flake graphite contents and different current levels on copper friction pairs were also studied. This provides a valuable reference for the selection of P/M composite materials for subway power transmission.

2. Experiments

2.1. Preparation of copper-flake graphite composite material

In order to add high volume fraction flake graphite in composite material, the mixed graphite clusters combined with pure iron powder were prepared using powder rolling, using the mixture of flake graphite and the pure iron powder. The flake graphite/copper matrix composite material were prepared by powder metallurgy. The composite material matrix consisted of several metal powders, including copper, chromium, nickel, and tin. The powders were evenly mixed for 4 h through a v-type mixer. Among them, the mass percentages of Cr, Sn, and Ni are 4%, 6%, and 1%, respectively. The flake graphite content was added with 1.8 wt%, 2 wt%, and 2.5 wt%, respectively. The well-mixed powder was placed in a steel mold and cold-pressed at 600 Mpa for 2 min to obtain a green body. The green body is sintered at 800 °C to 925 °C under an ammonia decomposition atmosphere to finally obtain three different graphite content GC/Cu P/M materials.

2.2. Mechanical performance test

The samples were processed, and the surface was polished to reduce the measurement error, and the density was measured by an electronic solid density meter (MH-3005A). By experiment using models for HBV-30 a cloth d durometer measure the hardness of materials powder metallurgy skateboarding, indenter diameter of 1 mm, will head to 10 kilograms of load pressure into the pantographed slide copper base composites on the surface of the sample and maintain pressure unloading after 30 s, every sample needs to measure more than five points, finally, take the average. The current and voltage were measured using an Agilent 34401A digital multimeter, and the resistivity of the material was determined using the kelvin method. The tensile strength of the sample was measured using a WE-300 universal material testing machine. The impact toughness test was performed using a NI150 metal pendulum impact tester.

2.3. Material characterization

The phase was observed by x-ray diffraction (D/Max 2500 V) with a 3° min⁻¹ scan rate and a scan range of 30° to 80°. The fracture morphology of the material was analyzed by a field emission scanning electron microscope (Zeiss SIGMA), and its chemical composition was measured by an energy spectrometer (Oxford, INCA).

2.4. Friction test

2.4.1. Mechanical friction test

The tests were carried out with loads of 15 N, 25 N, 35 N, and 45 N, respectively. Each test lasted 2 h, the shaft speed was maintained at 400 r min⁻¹, the real-time friction coefficient was recorded every second, and the sample mass before and after the experiment was recorded. The balance of torque measures the friction coefficient. The driven and active special arc tooth belt pulleys are installed on the main shaft and the motor. The constant torque servo motor and closed-loop speed regulation system make it have high transmission torque at low speed.

\[ f = \mu \cdot P \]  
\[ T = f \cdot r \]  
\[ \mu = \frac{T}{P \cdot r} \]
Where, $f$ is the friction force (N), $\mu$ is the friction coefficient, $P$ is the axial test force of the testing machine, $T$ is the testing machine friction torque (N·m), and $r$ is the trajectory radius of the contact point between the disc sample and the pin (m).

2.4.2. Current-carrying friction test

The current-carrying friction test of the sample was tested using ring-block pairs. The experimental instrument is a current-carrying friction test machine made in our laboratory, and its schematic diagram is shown in figure 1. The following formula can express the coefficient of friction:

$$P = \frac{T \cdot n}{9550}$$

$$\mu = \frac{P_1 - P_0}{N \cdot F \cdot v}$$

Where, $T$ is the torque of the transfer (N·m), $n$ is the transfer speed (r min$^{-1}$), $\mu$ is the friction coefficient, $P_1$ is the load power (W), $P_0$ is the no-load power (W), $N$ is the number of samples, $F$ is the load applied on the samples (N), and $v$ is the sliding speed (m s$^{-1}$).

3. Results and discussion

3.1. Mechanical properties

Figure 2 shows the impact fracture morphology of three different graphite clusters of content composite material. Figures 2(a)–(c) shows 100-fold SEM images of the fracture patterns of sample 1, 2 and 3, respectively. From the three figures, we can observe that some of the dimples are more evenly distributed in the copper matrix. There is a certain difference in the number, the number of dimples in sample 1 is larger, the number of dimples in sample 2 is second, and the number of dimples in sample 3 is the least. The dimple is an important microscopic feature to judge whether the fracture of a material is a plastic fracture. The existence of the dimple indicates the excellent condition of the plasticity of the materials [19]. Observation from figure 2, the number of dimples can also be inferred from the side. The impact toughness of sample 1 is the best because it can be seen from the figure that the number of dimples of sample 1 is more than that of the two others, and the dimples of samples are also deeper so that the material can absorb relatively more energy under the influence of external impact, and increase the ability to absorb energy at the time of fracture, thereby improving the impact toughness of the material [20]. Figures 2(d) and (e) are the magnified images of sample 2, it can be seen that the flake graphite is distributed in the matrix and is separated from the matrix during stretching, and some pores can also be observed, which may be due to these three following reasons: (1) the material forms a gap when the fracture occurs. (2) the sintered residual hole formed by the material during the sintering due to no shrinkage. and (3) the residual hole formed by the migration of the alloying element during sintering.
Figure 2 shows that the diffraction peaks of the copper elements in the XRD patterns of the three copper-based powder metallurgy slide materials are basically the same, and the graphite does not chemically react with or dissolve in the copper composite material matrix, but only exists as a single phase in the copper. In the composite material matrix, the diffraction peak intensity is weak due to the small content. After comparison with the standard copper peak, it is found that the diffraction peaks of copper in the three copper-based pantograph materials are shifted in the direction of decreasing angle. The main reason may be that the alloying elements in the copper matrix will form with copper. A certain amount of solid solution causes a change in the copper element’s lattice constant, causing lattice distortion, which causes the diffraction peak position of the copper-based powder metallurgy slide material to shift in the direction of decreasing angle [21]. It can be observed from the figure that the main phase of the composite material is Cu10Sn3, and intermetallic compounds such as Cu6Sn and Cu3Sn may be formed between Cu and Sn. Similar intermediate phases may be formed between the alloy elements, such as intermediate phases such as Ni3Fe. The Ni3Fe phase’s content is minimal so that the corresponding phase diffraction peak does not appear in the figure 2(f).

Table 1 shows the mechanical properties of the three samples having a graphite content of 1.8 wt%, 2 wt%, and 2.5 wt%, respectively. As the graphite content increased, the density decreased from 8.033 g cm\(^{-3}\) of sample 1 to 7.804 g cm\(^{-3}\) of sample 3, while the hardness decreased from 85.3 HB to 81.35 HB. When the graphite...
content is 2.5 wt%, the tensile strength and impact toughness is 147.96 MPa and 4.55 J cm$^{-2}$, respectively, much lower than that of 1.8 wt%. This is because graphite is insoluble in copper and graphite has poor wettability to copper [22]. The interface between copper and graphite can only be mechanical interlocking, and the bonding strength is low. When subjected to high load, the graphite particles are often peeled off or fall off, which severely restricts the composite material’s performance [23]. To improve the self-lubricity between copper and graphite, and to improve the anti-friction and wear resistance, the key is to enhance the wettability of copper composite material matrix and graphite, enhance its interface bonding, and matrix alloying is an effective way [24–26]. Adding an appropriate amount of chromium or other alloy elements into the copper matrix to reduce the surface tension by changing the copper composite material matrix’s chemical composition is an effective way to promote the wetting of the copper composite material matrix and graphite [27]. As the graphite content increases, the resistivity also increases, and the resistivity of the sample with a graphite content of 2.5 wt% reaches 0.227 $\mu\Omega$·m. On the one hand, the graphite resistivity itself is higher than that of copper, and on the other hand, the porosity generated during sintering also increases the resistivity.

### 3.2. Friction performance

The friction and wear performance are essential issues to be considered for the copper-based pantograph slides. Generally, the friction and wear performance determines the length of its service life, and its friction and wear performance research is of great significance [28–31]. In this work, the friction properties of copper matrix composite material are systematically studied by mechanical friction and current-carrying friction.

Figure 3(a) shows the wear rate of composite material with three different flake graphite contents and corresponding friction pairs under different loads. The wear rate here is defined as:

$$\delta = \frac{m}{l}$$

Where, $\delta$ is the wear rate of samples (mg m$^{-1}$), $m$ is the change of the sample mass before, and after the test (mg), $l$ is sliding distance (m). The results show that as the graphite content increased from 1.8 wt% to 2.5 wt%, the wear rate increased slightly. Simultaneously, the copper friction pair corresponding to the sample also increases as the graphite content in the sample increases. The copper friction pair corresponding to the sample with 1.8 wt% content has the lowest wear rate, which is very beneficial to prolong the service life of the copper contact wire. And for the same sample load increased from 15 N to 45 N, the wear rate of the sample and the corresponding copper ring also showed a positive correlation trend. As the load increases, the actual specific surface area of the contact increases, so the friction between the two sliding surfaces increases. It will grind softer materials at higher speeds due to contact friction with harder specific surface areas. At the same time, the increase in applied load also increases the stress on the friction surface, which also increases the weight loss and wear rate of the sample and the copper ring [32–34].

The average friction coefficient of different samples under different loads can be seen from figure 3(b). As the load increases, the friction coefficient increases, while, with the graphite content increasing, the friction coefficient decreases. The flake graphite is distributed in the matrix to provide a solid lubricating layer, which is very prone to shear deformation to the surface of the friction pair. As the graphite increases, a continuous and complete solid lubricating layer is formed, and the friction coefficient decreases. When adding solid graphite lubrication, such as particles in a metal matrix, the mutual movement extrusion due to the friction and heat effect, make its solid lubricant in a relatively stable sliding surface forming a layer of lubrication film, and by itself ‘consumable’ to constantly supplement and provide solid lubricant, repair the torn or cut the lubrication film, so as to achieve the lubrication and friction, changed the contact form of friction pair and reduce the friction coefficient. However, excessive addition of flake graphite causes a decrease in mechanical properties of the matrix, and a decrease in density, hardness, and friction properties. At higher loads, the surface of the composite material will be plastically deformed, and the lubricant and wear debris will also separate and peel off, increasing the wear rate. Excessive wear debris can damage the lubrication film on the worn surface, resulting in an increased friction coefficient [35–37]. Adding a small amount of Fe and Cr as hardening particles in the matrix can improve the matrix properties, reduce surface wear, and improve the service life of the material [38, 39].

Figure 3(c) gives the real-time curve of the friction coefficient of different samples under 25 N load, which shows that the curve of sample 1 fluctuates the most. The sample 2 and 3 start to fluctuate greatly, and then the

| Samples | Density (g cm$^{-3}$) | Electrical resistivity ($\mu\Omega$·m) | Hardness (HB) | Tensile strength (Mpa) | Impact toughness (J cm$^{-2}$) |
|---------|-----------------------|--------------------------------------|--------------|-----------------------|-------------------------------|
| 1       | 8.033                 | 0.195                                | 85.3         | 175.24                | 6.45                          |
| 2       | 7.963                 | 0.207                                | 84           | 158.67                | 5.5                           |
| 3       | 7.804                 | 0.227                                | 81.35        | 147.96                | 4.55                          |
subsequent tends to be stable. This is due to the low graphite content of sample 1 (1.8 wt%), which makes it impossible to form a continuous graphite lubricant film on the worn surface. The high hardness of the matrix also leads to severe wear on the composite material surface. When the flake graphite content can form a continuous lubrication film on the surface, the friction coefficient of the composite material begins to decrease [40]. However, too much graphite will reduce the properties of composites and increase the wear rate. The wear rate of the 2.5 wt% graphite sample under the 45 N load is twice that of the 1.8 wt% sample.

Figure 3(d) shows the zigzag curve of Sample 3 over a 45 N load for 900–1500 s. From the picture, we can get such information that the friction coefficient exhibits regular sinusoidal fluctuation with increasing time, and there is a slight upward trend. At the initial stage of friction, the graphite abrasives just produced adhere to the wear surface under the action of friction to form a graphite lubricating film, which effectively reduces the friction coefficient of the material and reduces the friction coefficient. Then, as the composite material wear debris increases, the hard abrasive chips quickly break through the graphite lubricating film, and even some of them are embedded in the wear surface, resulting in a large increase in the friction coefficient, which is often accompanied by the adhesion between the friction material and the dual member. It is worn, but it will soon be torn under the action of shearing force. Then, the graphite lubricating film is formed again, and the wear condition of the wear surface is deteriorated due to the accumulation of a large amount of composite material wear debris so that the overall appearance tends to rise slightly. This phase of presenting a regular curve is often referred to as the steady-state sliding phase [41, 42].

Figures 4(a)–(c) are SEM images of the friction and wear surfaces of copper rings corresponding to samples 1, 2, and 3 under 35 N load, respectively. In the picture, we can clearly find out that wear surface of three kinds of copper-based pantograph slide materials with different graphite content is characterized by adhesive wear, such as the marks produced by plastic deformation and the marks left by furrows after severe wear [43]. We can see from figures 4(a) and (b) that a large number of wear debris appears on the worn surface, indicating that the wear is more serious. As shown in figure 4(c), due to the high content of flaky graphite in sample 3, the friction surface between sample 3 and the copper ring is more likely to form a lubricant layer during friction, thereby reducing the generation of grooves and wear debris. Figure 4(d) is an enlarged view of the copper ring’s worn surface corresponding to sample 3. It can be found that many delamination phenomena occur due to plastic deformation.

Figures 5(a)–(c) show the wear surface topography of the copper ring corresponding to sample 2 under 25 N, 35 N, and 45 N loads, respectively as can be seen from the figures, as the load increases, the surface marks and
Figure 4. SEM micrographs of the worn surface of the Cu/CG alloys (a) copper ring corresponding to sample 1, (b) copper ring corresponding to sample 2, (c) copper ring corresponding to sample 3 under 35 N, respectively. (d) 400× magnified image of copper ring corresponding to sample 3 under 35 N.

Figure 5. SEM micrographs of the worn surface of copper ring corresponding to sample 2 at (a) 25 N, (b) 35 N, (c) 45 N, (d) 400× magnified image of contact wire under 45 N load.
furrows of the friction increase more and more, because the lubricating layer is damaged by the grinding debris under the load, resulting in a more severe friction environment. Figure 5(d) shows a 400× SEM image of the copper ring corresponding to sample 2 under a 45 N load, and it is apparent that abrasive debris adheres to the surface. These free hard particles slide between the two friction surfaces, similar to abrasive action, and are commonly referred to as three-body abrasive wear. The three-body worn abrasive particles create very high contact stress with the friction surface, which causes plastic deformation or fatigue on the friction surface [44].

Wear and tear (adhesive wear) are often accompanied by material transfer, which is an important phenomenon [45–48]. Figure 6 gives the elemental energy-dispersive x-ray spectroscopy (EDX) of the friction surface. Figure 6(b) is an EDS image after the test of sample 3, and it can be found that there is a distinct oxygen peak. This is because the high temperature generated during the rubbing process causes oxidation of the metal on the surface of the test sample. Figure 6(d) shows the EDS image of the copper ring in the wear test. The peaks of O, Fe, and Sn can be seen from the image, indicating that oxidative wear and material transfer occurred during the wear process. During the adhesive wear process, the material sheared off at the bond may move from one
surface to the mating surface during continuous motion. Combining the above figures shows that in the process of mechanical wear, the main wear is mainly adhesive wear, abrasive wear, and oxidative wear [49].

Figure 7(a) indicates the wear rate of the three samples and their corresponding copper rings at different electric currents. Figure 7(c) shows the variation of the coefficient of friction of the sample 3 at different currents, respectively. From the two figures, it can be seen that the interference of the current obviously deteriorates the friction and wear performance of the material. With the current intervention, the friction coefficient is obviously reduced, but the wear is greatly increased, and this effect is more significant with the increase of the current. The current flows through the frictional contact surface, generating contact arc heat and resistance heat, causing the contact surface temperature to rise and soften the material surface, thereby reducing friction coefficient. At the same time, an increase in the contact pair’s surface temperature will cause the surface of the material to oxidize, thus gradually forming an oxide film with a lubricating effect, which will cause the friction coefficient to decrease again. In the absence of an electric current, the contact pair is mainly mechanical wear (abrasive wear and adhesive wear), which causes little damage to the friction pair material and thus less wear. After the addition of the current, electrical wear (oxidation wear and arc ablation) occurs in the case of the original mechanical wear, and electrical wear is much larger than mechanical wear. As a result, the amount of wear in the case of electric current is much greater than that in the case of no current [28, 50–52]. From figure 7(a), we can also see that the wear rate of the sample and the copper ring increase with the current growth. Among the samples, Sample 1 has the lowest wear rate. Among the copper rings, the wear rate of the copper ring corresponding to sample 2 is the smallest. This may be because the graphite content increases the chance of forming a lubricating film, but too high graphite content will reduce the matrix strength. It makes it easier for abrasive particles to draw grooves and improve the wear rate. Figure 7(b) shows the friction coefficient curves of different samples at 20 A current. It can be shown that the friction coefficient is stable and fluctuates within a certain range, and the fluctuation range is between 0.3 and 0.4. The fluctuation of friction coefficient is the true embodiment of the relative sliding, impact, and vibration of the friction pair [53]. And figure 7(d) is the EDS image of sample 3 after the current-carrying wear test. The oxygen peaks appearing in (d) indicate that oxidative wear has occurred.

Figure 7. (a) Wear rate of three samples at different currents, (b) Comparison of friction coefficient of three samples with time under 20 A, (c) Immediate friction coefficient curve of sample 3 under 0 A, 10 A, 20 A and 30 A respectively, (d) EDS results of sample 3 after Current carrying wear.
Figures 8(a)–(c) are the wear surface morphology of three different samples at 30 A, and figure 8(d) is the 400× magnification wear surface morphology of Sample 3 at 30 A, respectively. Figures 8(a)–(c) show obvious furrow, indicating that abrasive wear has occurred, and there are some adhesive pits and plastic deformation on the worn surface, meaning adhesive wear. A small amount of ablation pits on the worn surface can also be observed in figure 8(e), indicating that electrical wear has occurred. Electrical wear mainly includes local melting and arc erosion caused by resistance heat, which is an essential factor causing serious wear of materials [42]. The addition of chromium to the composite material reduces the electrical conductivity of the copper composite material and reduces arc generation when the copper composite material is energized [54].

Figure 9 shows the arc condition of Sample 2 at different currents. It can be seen that a stable arc can be observed through the eyes under the conditions of 20 A and 30 A. Arc is one of the essential phenomena of the current generation in the process of current-carrying friction and wear. In the current-carrying friction and wear
process, due to the poor contact between the friction pairs, an offline arc is formed to cause arc erosion on the surface, which exacerbates the softening of the contact points and even the phenomenon of adhesion welding, thus greatly reducing the surface quality and causing wear. Performance deteriorates. Arc erosion severely damages the friction contact surface, while consuming friction material, it significantly increases the amount of flow and wear of the slider and the wire. It can also be observed in figure 7 that the wear rate of the copper ring increases rapidly from 10 A to 20 A due to arc erosion.

4. Conclusion

The high-graphite copper-based composite material was prepared by the powder metallurgy method. The elements such as Sn, Ni, Fe, and Cr were uniformly distributed in the copper composite material matrix. The phase composition of the copper composite material matrix was Cu_{10}Sn_{3} and the flake graphite. Among the three samples, the tensile strength and impact toughness of the sample with 1.8 wt% graphite content were 175.24 MPa and 6.45 J cm^{-2}, respectively, and had excellent mechanical properties. The flake graphite uniformly dispersed as clusters in the copper matrix, mainly for lubricating and antifriction, and does not react with the copper matrix.

During mechanical wear, as the graphite content in the flake increases, the friction coefficient decreases, and the wear rate increases slightly. The wear rate of the copper ring is also affected by the graphite content. The wear rate of the copper ring with the graphite content of 1.8 wt% is the lowest, and the wear rate of the copper ring under a load of 45 N is 0.021 mg m^{-1}, which means that its service life is longer. Mechanical wear is mainly caused by abrasive wear, adhesive wear, and oxidative wear.

In the current-carrying wear process, the wear rate is greatly affected by the current, and the current will accelerate wear. The wear rate of the copper ring corresponding to the sample with a graphite content of 2 wt% is the smallest at all three currents, and the wear rate at a current of 20 A is 0.038 mg m^{-1}. Current-carrying wear is mainly caused by adhesive wear, electrical wear, and oxidative wear. The wear rate during current-carrying wear is several times that when there is no current, which is caused by arc ablation. The occurrence of an arc causes an increase in the amount of wear and is accompanied by adhesive wear and material transfer.

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References

[1] Moustafa K B, El-Badry S F and Sanad A M S A 2002 Friction and wear of copper-graphite composites made with Cu-coated and uncoated graphite powder Wear 253 699–710
[2] Dong R, Cui Z, Zhu S, Xu X and Yang X 2014 Preparation, characterization and mechanical properties of Cu–Sn alloy/graphite composites Metallurgical and Materials Transactions A 45 5194–200
[3] Singh M K and Gautam R K 2018 Mechanical and tribological properties of plastically deformed copper metal matrix nano composite Materials Today: Proceedings 5 5727–36
[4] Akharpour M R, Alipour S, Safarzadeh A and Kim H S 2019 Wear and friction behavior of self-lubricating hybrid Cu-(SiC + x CNT) composites Composites Part B: Engineering 158 92–101
[5] Somani N, Tyagi Y K, Kumar P, Srivastava V and Bhowmick H 2018 Enhanced tribological properties of SiC reinforced copper metal matrix composites Mater. Res. Express 6 016549
[6] UL Haq M and Anand A 2018 Dry sliding friction and wear behaviour of hybrid AA7075/Si3N4/Gr self lubricating composites Mater. Res. Express 5 066544
[7] Shafqat, S., Anand, R., Ifran Ul Haq M., Raina A., Mohan S., Kumar R., and Anand A. 2020 Friction and wear behaviour of AA2024/ZrO2 composites: effect of graphite Recent Advances in Mechanical Engineering ed H Kumar and P K Jain (Singapore: Springer Singapore) pp 597–601
[8] Gupta M K 2019 Analysis of tribological behavior of Al/Gr/MoS2 surface composite fabricated by friction stir process Carbon Letters (https://doi.org/10.1007/s10584-019-00109-w)
[9] Gupta A, Mohan S, Anand A, Haq M I U, Raina A, Kumar R, Singh R A, Jayalakshmi S and Kamal M 2019 Tribological behaviour of Fe–C–Ni self-lubricating composites with WS2 solid lubricant Mater. Res. Express 6 126507
[10] An Z, Ohi A, Hirai M, Kusaka M and Iwami M 2001 Study of the reaction at Cu/3C–SiC interface Surf. Sci. 493 182–7
[11] Dorfman S, Mundim K C, Fuku D, Berner A, Ellis D E and Van Humbeeck J, 2001 Atomistic study of interaction zone at copper–carbon interfaces Materials Science and Engineering: C 15 191–3
[12] Chen B-B, Chen S, Yang J, Li H-P, Guo S, Tang H and Li C-S 2015 Tribological properties of Cu-based composites with S-doped NbSe_2, Rare Met. 34 407–12

[13] Gao X, Yue H, Guo E, Zhang S, Yao L, Lin X, Wang B and Guan E 2018 Tribological properties of copper matrix composites reinforced with homogeneously dispersed graphene nanosheets Journal of Materials Science & Technology 34 1925–31

[14] Xu E, Huang J, Li Y, Zhu Z, Cheng M, Li D, Zhong H, Liu J and Jiang Y 2019 Graphite cluster/copper-based powder metallurgy composite for pantograph slider with well-behaved mechanical and wear performance Powder Technol. 344 551–60

[15] Meddah S, Chaddi H, Boureiba M, Montagao A, Iost A, Labaz M and Taleb A 2020 Dry sliding wear performance of an annealed TiNi alloy with different nickel contents Mater. Res. Express 7 036508

[16] Tu C J, Chen D, Chen Z H and Xia J T 2008 Improving the tribological behavior of graphite/Cu matrix self-lubricating composite contact strip by electroplating Zn on graphite Tribol. Lett. 31 91–8

[17] Fu X, Hu Y, Peng G and Tao J 2017 Effect of reinforcement content on the density, mechanical and tribological properties of Ti_5Si_3C/Al_2O_3 hybrid reinforced copper-matrix pantograph slide Science and Engineering of Composite Materials 24 807–15

[18] Jiang X, Fang H C, Xiao P, Liu T, Zhu J M, Wang Y C, Liu P F and Li Y 2018 Influence of carbon coating with phenolic resin in natural graphite on the microstructures and properties of graphite/copper composites J. Alloys Compd. 744 165–73

[19] Konovalenko I, Maruschak P, Brezinová J and Brezina J 2019 Morphological characteristics of dimples of ductile fracture of VT23M alloy and identification of dimples on fractographs of different scale Materials (Basel) 12 2051

[20] Ohashi M 2007 Extreme value analysis of ductile fracture surface by dimpled rupture associated with fracture behavior of tensile specimens J. Mater. Sci. 42 9877–87

[21] Novelo-Peralta O, González G and Lara-Rodríguez GA 2008 Characterization of precipitation in Al-Mg–Cu alloys by x-ray diffraction peak broadening analysis Mater. Charact. 59 773–80

[22] Wang P, Zhang H, Yin J, Xiong X, Deng C and Wu X 2018 Effect of pyrolytic carbon interface thickness on conductivity and mechanical and wear properties of copper mesh modified carbon/carbon composite Mater. Des. 154 302–11

[23] Dorfman S and Fuks D 1995 Carbon diffusion in copper-based metal matrix composites Sens. Actuators A 51 13–6

[24] Fu W, Hu S P, Song X G, Li J X, Cao J, Feng J C and Wang G D 2017 Wettability and bonding of graphite by Sm_53Al_46.5Cu TiAlloys Carbon 121 536–43

[25] Xiao J, Wu Y, Zhang W, Chen J and Zhang C 2019 Friction of metal-matrix self-lubricating composites: relationships among lubricant content, lubricating film coverage, and friction coefficient Friction 8 517–30

[26] Jin H et al 2019 Comparative tribological behavior of matrix composites containing natural graphite and expanded graphite Friction 8 684–94

[27] Wang Y, Yan Q-Z, Zhang F-F, Ge C-C, Zhang X-L and Zhao H-Q 2013 Sintering behavior of Cu-SiO_2 and Cu-Cr metal matrix composites J. Alloys Compd. 536 319–24

[28] Ashiri R, Niroumand B and Karimiradzeh F 2014 Physical, mechanical and dry sliding wear properties of an Al–Si–Mg–Ni–Cu alloy under different processing conditions J. Alloys Compd. 582 213–22

[29] Gong T, Yao P, Xiong X, Zhou H, Zhang Z, Xiao Y, Zhao L and Deng M 2019 Microstructure and tribological behavior of interfaces in Cu-SiO_2 and Cu–Cr metal matrix composites J. Alloys Compd. 786 975–85

[30] Gao Y, Jie J-C, Zhang P-C, Zhang J, Wang T-M and Li T-T 2015 Wear behavior of high strength and high conductivity Cu alloys under dry sliding Transactions of Nonferrous Metals Society of China 25 2293–300

[31] Jia P, Gauzlan R K and Tyagi R 2017 Friction and wear behavior of Cu–4 wt.%Ni–TiC composites under dry sliding conditions Friction 5 437–46

[32] Lei Y, Jiang J, Bi T and Wei Z 2018 Effect of counterparts and applied load on the tribological behavior of the graphite–nickel matrix self-lubricating composite Tribol. Lett. 66 129

[33] Ren S, Chen J, He X and Qu X 2018 Effect of matrix–alloying-element chromium on the microstructure and properties of graphite flakes/copper composites fabricated by hot pressing sintering Carbon 127 412–23

[34] Zhang P, Zhang L, Wei D, Wu P, Cao J, Shijia C, Xu Q and Fu K 2019 The synergistic effect of Cr and CrFe particles on the braking behavior of Cu-based powder metallurgy brake pads Tribol. Trans. 62 1072–85

[35] Luo B, Liu C, Xu Y and Zhang L 2020 Effect of expanded graphite on the tribological behavior of tin–bronce fiber brushes sliding against brass Tribol. Trans. 63 61–8

[36] Moskhovich A, Perfiliev V, Lapsker I and Rapoport L 2010 Stribeck curve under friction of copper samples in the steady friction state Tribol. Lett. 37 645–53

[37] Moskhovich A, Perfiliev V, Meshi L, Samuha S, Cohen S, Cohen H, Laiktman A and Rapoport L 2012 Friction, wear and structure of Cu samples in the lubricated steady friction state Tribol. Int. 46 154–60

[38] Mishina H and Hase A 2019 Effect of the adhesion force on the equation of adhesive wear and the generation process of wear elements in adhesive wear of metals Wear 432–433 202936

[39] AsadiKouhanjani S, ZarehBidaki A and Akbari A 2009 The effect of sliding speed and amount of loading on friction and wear behavior of Cu–0.65 wt.%Cr alloy J. Alloys Compd. 486 319–24

[40] Wang P, Zhang H, Yin J, Xiong X, Deng C and Wu X 2018 Effect of pyrolytic carbon interface thickness on conductivity and mechanical and wear properties of copper mesh modified carbon/carbon composite Mater. Des. 154 302–11

[41] Kostas M, Jovanovic I and Vukmirovic F 1999 The effect of Cr addition on the friction and wear behavior of Ni–TiC composite Materials (Basel) 12 1021

[42] Meddah S, Chaddi H, Boureiba M, Montagao A, Iost A, Labaz M and Taleb A 2020 Dry sliding wear performance of an annealed TiNi alloy with different nickel contents Mater. Res. Express 7 036508

[43] Tu C J, Chen D, Chen Z H and Xia J T 2008 Improving the tribological behavior of graphite/Cu matrix self-lubricating composite contact strip by electroplating Zn on graphite Tribol. Lett. 31 91–8

[44] Wang P, Zhang H, Yin J, Xiong X, Deng C and Wu X 2018 Effect of pyrolytic carbon interface thickness on conductivity and mechanical and wear properties of copper mesh modified carbon/carbon composite Mater. Des. 154 302–11

[45] Kostas M, Jovanovic I and Vukmirovic F 1999 The effect of Cr addition on the friction and wear behavior of Ni–TiC composite Materials (Basel) 12 1021

[46] Westlund V, Heinrichs J and Jacobson S 2018 On the role of material transfer in friction between metals: initial phenomena and effects of roughness and boundary lubrication in sliding between aluminium and tool steels Tribol. Lett. 66 97

[47] Xue W, Gao S, Duan D, Zhang J, Liu Y and Li S 2018 Material transfer behavior between a blade and two types of coating during high-speed rubbing Tribol. Trans. 61 827–41

[48] Ding T, Chen G X, Bu J and Zhang W H 2011 Effect of temperature and arc discharge on friction and wear behaviours of copper strip/ copper contact wire in pantograph–catenary systems Wear 271 1629–36

[49] Rigney D A 2000 Transfer, mixing and associated chemical and mechanical processes during the sliding of ductile materials Wear 245 1–9
[49] Mushtaq S and Wani M F 2018 High-temperature friction and wear studies of Fe-Cu-Sn alloy with graphite as solid lubricant under dry sliding conditions Mater. Res. Express 5 026504

[50] Ding T, Chen G X, Wang X, Zhu M H, Zhang W H and Zhou W X 2011 Friction and wear behavior of pure carbon strip sliding against copper contact wire under AC passage at high speeds Tribol. Int. 44 437–44

[51] Lin X-Z, Zhu M-H, Mo J-L, Chen G-X, Jin X-S and Zhou Z-R 2011 Tribological and electric-arc behaviors of carbon/copper pair during sliding friction process with electric current applied Transactions of Nonferrous Metals Society of China 21 292–9

[52] Zhang Y, Yang Z, Song K, Pang X and Shangguan B 2013 Triboelectric behaviors of materials under high speeds and large currents Friction 1 259–70

[53] Kim W, Wang Q, Liu S and Asta M 2006 Simulation of steady and unsteady state surface temperature under sliding imperfect electrical contact between rough surfaces Proc. of the 23rd Int. Conf. on Electrical Contacts 226–31

[54] Ranjbar M, Ahadian M M, Iraji zad A and Dolati A 2006 The effect of the Cr and Mo on the surface accumulation of copper in the electrodeposited Ni–Fe/Cu alloy films Materials Science and Engineering: B 127 17–21