The Micro-Tribological Behavior and Friction Mechanism of the Graphite/Cu Composites and Copper-coated Graphite-graphite/Cu Composites

Mao-Zhong Yi (✉ yimaozhong@126.com)
Central South University
Linying Zhu
Central South University
Bei Zhang
Central South University
Aolin Xie
Central South University

Research Article

Keywords: G/Cu composites, copper-coated graphite(CCG), CCG-G/Cu composites, micro-tribological behavior, friction mechanism

Posted Date: March 5th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-271448/v1

Abstract

The ring-block tribological behavior of the graphite/Cu(G/Cu) composites and copper-coated graphite-graphite/Cu(CCG-G/Cu) were studied by observing the friction coefficient,wear rate,microstructure and morphogoly of the composites after friction experiments.SEM and TEM were used to character the micro-morphology and micro-structure of debris,friction surface and friction cross section of the composites.The results show that adding 20wt% copper-coated graphite could reduced the friction coefficient and wear rate of the composites.The micro-morphology and micro-structure show that the copper phase are undergo oxidation and plastic deformation under cyclic stress,results in abundant deformation area in copper-rich zones.Interlaminar shedding and intramolecular tearing occurs in graphite phase,and then laid flat on the friction surface,forming a friction film with higher integrity and reducing the friction coefficient of the composites.The TEM images of the friction cross section show that deformation zone is mainly composed of accumulation zone,drag zone and carbon film.The simulation of the friction process shows that the initial stage is mainly dominated by abrasive wear and adhesive wear.With the progress of the experiment,the exposed copper phase is oxidized and oxidative wear occurs,graphite is shed and transferred to the contact surface.In the later stage of the experiment,a complete friction film with high graphite content is formed on the contact surface,which is mainly dominated by fatigue wear.

Introduction

The G/Cu composite material has the self-lubricating property[1] of the graphite,the excellent thermal and electrical properties of copper[2, 3],so it is widely used in the preparation of lubricating materials[4],sealing materials and electric contact materials such as commutators,brushes,and pantograph carbon skateboards[5, 6].As lubricating materials,excellent friction and wear properties, thermal conductivity and certain mechanical properties are required.As an important application field of graphite/copper composites,electric contact materials need to have excellent electrical conductivity[7] and friction and wear properties[8].In the process of friction,the friction layer can be formed quickly and the friction heat can be dissipated quickly,so as to ensure the integrity of the friction film.

Because of the poor wettability between graphite phase and copper phase[9],each phase of the composites can only be connected by mechanical bounding and physical bonding,resulting in the poor binding effect between the two phases and there are voids existing in the composites[10],which seriously affects the mechanical properties and wear-resisting property of the composites.To improve the bonding strength and enhance the properties of the composites,some measures such as the addition of alloying elements which are prone to form carbides[11],the addition of new carbon material reinforcing agents and the modification of the graphite surface have been taken[12].Many scholars have improved the mechanical properties and friction properties of composites by adding appropriate new high-performance materials such as carbon nanotubes(CNTs)[13],carbon fibers(CF)[1] and graphene[14, 15].However,the nano-materials are prone to agglomeration due to the high surface activity[16],which limits the amount and application fields of nano-materials.Metal coating on the surface of carbon material is a feasible method to improve the bonding strength[17].Numerous studies show that the copper,nickel[18] and silver coating on the surface of carbon materials can availably improve the bonding strength between the strengthened graphite and metal phases.After a lot of research and exploration,the technology of preparing metal-coated graphite has become mature,the preparation cost of the composites have also been reduced,which can be effectively applied in industrial preparation.Wear resistance is an important property that affects the use of G/Cu composite materials[19].A large number of scholars have studied the friction and wear performance of C/Cu composites and the reinforcement materials in different conditions from macro perspective[20, 21],the friction mechanisms are derived by observing the friction coefficient,wear rate and SEM diagrams[22].But few studies have observed the morphology,structure and crystal changes before and after the friction experiment from the micro perspective.

In respect of the issues above,G/Cu composites with different content of CCG were producted by powder metallurgic method,and the effects of CCG on physical properties and tribology behavior of the samples after ring-block friction and wear experiment were researched.The crystal structures and micro-morphology of the debris,friction surface and friction cross section of the composites after were studied by means of fine analysis method such as SEM and TEM.Based on the above information,the friction mechanism of composites in each friction stage is deduced.

Materials And Experiments

2.1 Materials

The grain diamater of electrolytic copper powders and graphite used during the study are about 50μm and 150μm,respectively.CCG was prepared by electroless plating,and the specific physical parameters of the coated graphite are listed in Tab.1.

Tab.1 Physical parameters of the CCG

Raw materials	Grain size(μm)	Coating thickness(μm)	Coating content(mass fraction,%)	Coating way
Copper-coated graphite	100~150	0.5~2	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 10wt% to 50wt% with a gradient of 10wt%.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 powder metallurgy method.The experimental parameters are as follows:the pressing pressure is 300MPa,the sintering temperature is

780℃,and the sintering time is 2h.After sintering,took out the samples and store it sealed for subsequent experiments.

2.3 Test procedures

MM-2000 ring-block friction testing machine was used to perform tests of the G/Cu and CCG-G/Cu composites.To meet the experimental needs,the surface of the composite was polished by sandpaper,until there are no significant groove marks.The experiments were carried out for 300 minutes under the conditions of 30N load and 0.42m/s sliding velocity,and pure copper ring with the outer diameter of 40mm and the inter diameter of 20mm were used as friction pairs in the experimental process.The wear was calculated by formulas(1) and(2):

$$W = 10\left(\mathrm{R}^2 \arcsin\frac{b}{2R} - \frac{b}{2}\sqrt{R^2}\right) \quad (1)$$

$$\omega = \frac{\mathrm{W}}{\mathrm{F}\times\mathrm{L}} \quad (2)$$

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

Microstructure and morphology of the debris,friction film and friction cross section of the composites were characterized by Tecnai G2 F20 TEM instrument.The debris was dispersed by ultrasonic treatment in alcohol for half an hour.In order to prepare the friction film,5%(mass fraction) PVA solution was first dropped on the friction surface,and then solidified for 24h at room temperature to form the PVA film.After careful tearing of the dried PVA film,PVA was dissolved in 90℃water bath,and the friction film was collected with a micro-grate for observation and analysis after drying.Helios Nanolab 600i double-beam electron microscope was used to cut the friction section with the thickness of 30~35nm along or perpendicular to the friction direction of the samples after the friction wear test by focused ion beam(FIB).

Results And Discussion

The poor wettability between graphite phase and copper phase can lead to the low bonding strength between them,which affects the properties of G/Cu(graphite/copper) composites.The addition of CCG not only enhances the bonding strength between graphite and copper phases,but also forms a more complete network structure between copper phases.

3.1 Mechanical properties

The mechanical properties of G/Cu composites have a certain influnce on the triblology behavior of composites.When the friction pair is fixed,mechanical properties affect friction mechanism of the composites,like the forming speed of friction film and the wear rate.Under normal circumstances,when the hardness of composite material is high,it will lead to serious abrasive wear at the beginning of the experiment.When the mechanical property is poor,it will have a deep impact on the fatigue wear at the later stage,resulting in a higher wear rate.The mechanical properties of the CCG-G/Cu(copper-coated graphite-graphite/copper) composites are listed in Fig.1,and the CCG ranges from 0wt% to 50wt%.The results show that because of the low strength and large particle size of CCG,the hardness and bending strength of the composites decrease with the increase of CCG content.

3.2 Micro-morphology of composites

The microstructure and morphologies of G/Cu composites and CCG-G/Cu composites are shown in Fig.2.Mainly studied the composites with CCG from 0wt% to 50wt%,and the total graphite phase content remains unchanged at 50wt%.Fig.2(a)(G/Cu composites) and Fig.2(b)(CCG-G/Cu composites) show that the copper and graphite are more easy to agglomerate because of the density difference,the splitting effect of the graphite on the copper phase prevents the copper phase from connecting to each other.There are fractures in the network structure formed by the connection between the copper phase in the graphite-rich area.As the content of CCG continues to increase,the copper coating and CCG which with large particle size contribute to the formation of more complete and continuous network copper structure.It formed the conduction and thermal channels,which can dissipate the friction heat generated in the friction process.

3.3 Tribology behavior

3.3.1 Friction coefficient and wear rate

After 300min ring-block friction and wear experiment,the friction coefficient and wear rate of the G/Cu composites and CCG-G/Cu composites are shown in Fig.3.The friction coefficient and wear rate of two kinds of materials show that the CCG content makes a big difference on tribological properties of the composites.As the content of CCG increases from 10wt% to 50wt%,the friction coefficient of the composites increases from 0.203 to 0.207 first and then decreases to 0.16,the friction coefficient of the composites is basically unchanged when the addition amount of CCG is 10wt%,and then decreases sharply when its content increase to 20wt%.The content of the CCG with large particle size on the surface is lower when the addition amount is small,it has little effect on the composition and integrity of the friction film on the surface.With the continuous increase of its content,the content of it spread on the surface increases,and it is more easily to fall of between layers and the coating under the action of the friction force during the friction process.

3.3.2 Micro-structure and micro-morphology of worn surface and debris

The information provided by the micro-morphology of worn surface and debris is helpful to infer wear mechanism during the friction process.The differences of friction micro-structure and composition cause to occur different friction mechanism,and eventually different surface micro-morphology is formed.SEM images EDS(Energy Disperse Spectroscopy) patterns show that compared with other kinds of composites(Fig.4(a)),20wt%CCG-G/Cu composites have friction film with fewer cracks and pits but abundant grooves along the frictional dicretion is formed on the worn surface.There are almost no abrasive chips with large particle size on the worn surface,and its total number is much less than that of other two kinds of composites.Its low hardness leads to hard microbumps scratch the sample under shear action and leave scratches on the surface,so the abrasive wear is more likely to occur on the friction surface in the initial friction process.This leads to abundant grooves produced on the friction surface caused by abrasive wear,but with few surface cracks and large holes caused by adhesive wear and fatigue wear on the surface.And the picture also shows that the friction film is well combined with the matrix,and it can effectively maintain the integrity and inhibit the renewal rate of the friction film.The SEM micrograms of 40wt%CCG-G/Cu composites(Fig.4(c) and (f)) show that the friction film formed on the contact surface is complete but has lower bonding strength with the matrix,there are a mass of long cracks on the surface,and there is a serious tendency to fall off.

To further verify the above conclusions,Tecnai G2 F20 type TEM instrument was used to characterize the crystal structure,micro-structure and micro-morphology of debris.

The microstructure and morphology of the debris of the G/Cu composites (Fig.5(a~c,f))and 20wt%CCG-G/Cu composites(Fig.5(d~e,g~i)) are shown in Fig.5.Morphology image of G/Cu composites (Fig.5(a)) show that the debris have various forms,some of which are formed by interlayer shedding of surface graphite under the action of shear force,and some of which are formed by rolling the accumulation fine chips under the action of furrow cutting,and some large particle size of the debris that fall off under the action of fatigue wear.The exfoliated lamellar graphite is relatively neat and its surface is flat without obvious folding.And its HRTEM image implies that its structure and the component is pure graphite,and due to the continuous cyclic stress,the graphite expanded and the spacing of the layers widened.The composition of the grinding chips near the red frame in Fig.5(a) is not uniform,and the edge of the grinding chips is relatively smooth and irregular,and the grinding chips are roughly elliptic.It can be inferred that the composition here is relatively complex,and graphite,copper and copper oxide coexist.Its HRTEM images(Fig.5(c and f)) display a great 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 is simply piled up by various components of finely grinding chips,and the deformation in this area is formed because the metal phase is plastic deformed under the action of friction force and friction heat,and then transferred to the contact surface,deformation degree in the edge of the debris is deeper because the spacing between the accumulated finely grinding chips is large,and it is easy to generate cracks here and extend along the friction direction,and finally fall off,and the results of Fast Fourier Transform(FFT) also show that there are many kinds of structural crystals in this region.Oxidative wear mainly occurs when there is exposed copper on the surface of the sample and friction pair,once a relatively complete friction film is formed on the surface,the possibility of oxidation wear is reduced.Adjacent copper and its oxide are easily connected to each other by plastic flow,part of the connecting metal oxides covered the graphite surface,which damaged the integrity of the graphite layer on the friction surface.Because of the poor wettability between copper phase and graphite phase,lamellar graphite structure near the interface cannot be stretched and tiled on the surface,which led to shrinkage,folding and even being torn.The accumulation of the damaged graphite,copper and its oxides caused the complex composition and structure of the area.

The TEM micrograms of the debris of the 20wt%CCG-G/Cu composites(Fig.5(d and e)) show that there are two kinds forms of debris:As shown in Fig.5(d),lamellar graphite with regular edges is formed by interlayer shedding of surface graphite particles under shear force.Fig.5(b) shows a debris accumulation layer with relatively smooth edges and uneven structural composition,and the content of such debris metal and its oxides is relatively high.The HRTEM image(Fig.5(g)) of the edge area of chip graphite in Fig.5(d) show that there are other crystals in this region besides graphite,graphite structure is destroyed under the effect of friction shear stress,causing graphite layer spacing increases,and leading to interlaminar fracture,finally formed the pieces of graphite,even form the disordered carbon material,as shown in I area.The HRTEM images of the accumulated debris in Fig.5(e) show that the content of copper and its oxide is high,the evidence of graphite is not obvious and there are a lot of deformation areas at the edge of the debris.The deformation areas with different sizes and deformation directions are attached to each other,and the grain boundaries with different spacing are formed.The degree of deformation determines the state of boundary connection,a wide crack between the two phases is formed when the crystal orientation of adjacent regions is different and the deformation degree is deep,and the two adjacent different phase are easy to be separated under the action of cyclic stress,cracks developed on the friction surface,which damage the surface friction layer.

The composition and crystal structure of the friction surface are similar to the debris,the SAED(Selected Area Electron Diffraction) spectra(Fig.6(a)) shows the crystal plane infromation of the diffracted crystal of friction,the presence of the copper oxides(such as CuO and $CuCO_3$)clearly show that oxidative wear occurs during the experiment,the copper and graphite phases are oxidized by oxygen in the air to form oxygen-containing compounds such as CO_2,CuO,Cu_2O and $CuCO_3$ when the surface temperature rises under the action of frictional heat.The high graphite content in the samples results in a complete and thick friction film on the contact surface.The morphological images of the G/Cu composites(Fig.6(b)) and the CCG-G/Cu composites(Fig.6(e)) show that the friction film made by stacking and pressing fine grinding chips of different sizes is relatively complete.The shape of the friction film formed by stacking is different,and the stacking direction is different,and the thickness is also significantly different.The friction film of the G/Cu composites is accumulated by fine grinding chips of different shapes and sizes layer by layer.The shape of the fine grinding chips in this area is relatively regular,and most of them are elliptic lamellae with large particle size range and smooth edges.Based on the above analysis,it is speculated that most of them are composed of copper and its oxide.Some sharp and neat long strip chips also can be seen on the surface,which are narrow and short,it 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 edge of the debris show that the graphite content is relatively high there,and the crystal structure of graphite is destroyed under the action of stress and shear force and some of them turns into disordered structure carbon.Because of poor bonding strength between graphite phase and copper oxides in debris,the cracks are more likely to occur there under the action of cyclic stress.The Fig.6(f~h) show 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 show that there are wide boundary gaps at the edge of the deformation area.As the experiment go on,the cracks are derived 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 - regeneration of the friction film in this area.

In contrast,the composites added 20wt%CCG has better friction and wear performance,the friction coefficient and wear rate of it is lower than G/Cu composites.This is because the friction film formed after the sheets of the graphite falling off from the surface of CCG are tiled on the friction surface has higher graphite content and better integrity,and the friction coefficient of composites is effectively reduced.Appropriate content of CCG(20wt%) can ensure that the friction surface has a certain strength,and the bonding strength with the matrix is not too weak.The thickness of the friction film formed is moderate,and the renewal speed of the friction layer is not too fast.Therefore, the wear rate of the composites is low.

3.3.3 Micro-structure and micro-morphology of friction cross section

The change of crystal structure,morphology and composition before and after the test can be compared more intuitively through the TEM images of friction cross section.And the friction layer,the friction secondary layer and the sample matrix can be clearly observed.

For G/Cu composites,its TEM micrograms of the friction cross section (Fig.7) show that there are deformation zone and non-deformation zone(matrix) in the longitudinal direction,and there is a great difference in the morphology and structure of the two regions.The structure of the matrix is uniform,and the graphite phase and copper phase maintain their complete structure without deformation.It can be seen from Fig.7(c) that the interface of the two phases is poor in wettability,resulting in low bonding strength of the two phases.The morphology image of the composites shows that the contact surface is seriously deformed after friction and wear test,and the graphite and copper phases are deformed and cross-linked under cyclic stress.Interlaminar shedding and intramolecular tearing occurs in graphite under shear action.Small particle size graphite from the orignal no specific direction the friction direction under the action of friction force.The change of the direction of each phase results in the increase of the spacing between particles and the cracks are easy to be derived,the softening plastic flow of copper phase flows into the cracks between the phases.Fig.7(e) shows that there are small pieces of metal and metal oxide phases between the graphite phases,and a mass of dislocation areas exist in the metal phase area.The partial enlargement in Fig.7(e) shows that this area is composed of a large number of crystal structures with different orientations,and there are obvious grain boundary between different crystals.The boundary spacing varies with the crystal structure and deformation degree,and there are obvious boundary regions between graphite phase and metal phase due to low binding strength,part of the graphite structure in the edge region is completely destroyed and becomes an invisible carbon structure.

In a word,the crystal structure of the friction surface changed after the friction and wear test.The graphite phase fell off between layers and tore within layers under the action of the frictional force,and the laminated deformed graphite lay flat on the friction surface to form a carbon film,which reduced the friction coefficient.Because of the softening of copper phase,a mass of deformation zones are formed due to plastic deformation.Due to different degrees of deformation,grain boundary cracks with different sizes are formed among different phases.When serious deformation occurs,wide cracks are formed and continue to extend until spall occurs under the action of cyclic stress.The main wear mechanism at this stage is fatigue wear.

For CCG-G/Cu composites,the TEM and HRTEM micrograms of its friction cross section show that because of the special contact mode of ring block friction and wear,the friction surface has different deformation strength under different stress time,the Fig.8(a) shows that the deformation area presents a triangular trend,and the deepest deformation can reach 2~3μm.The length of the deformation zone,crystal structure and composition on both sides of the center position are different due to the different force direction and magnitude.Along the direction of friction,the deformation is divided into the accumulation zone and the drag zone with the lowest point as the center.In front of the friction direction,attribute to the serious accumulation of grinding 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.In order to further study the difference of the structures in each region,the friction film I,stacking area and dragging area are analyzed with high resolution analysis method.

The HRTEM image(Fig.8(a)) of the friction film show that a heavily deformed thin layer of graphite is spread on the friction surface,and the graphite layer spacing expands under the cyclic stress.Close to the friction film area,the structure is damaged in a deep degree and independent massive metal oxides which formed by oxidation of copper appear.As the stress concentration point,the bonding effect between copper and other surrounding phases is destroyed and form a wide space,leading to the surface carbon film is prone to fall off.The graphite is extruded to the surface under shear action.The morphologies and structures of zone I(Fig.8(c)) and zone (Fig.8(d)) are similar,there are abundant metal rich areas with a lot of deformation areas,and the grain between graphite phase and metal phase are obvious.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 decreased and the interlaminar shedding occurred.The split of the oxide of copper broke the graphite and formed graphite fragments,even broken into amorphous carbon structures.In comparison,the graphite content is higher in the accumulation zone,because the graphite density is low and the graphite is easy to be transferred over a long distance until it encounters an uphill slope ahead of the friction on the friction surface,leading to the accumulation of grinding chips in this area.

3.3.4 Analysis of friction mechanism

Understanding the friction mechanism of composite materials can effectively take corresponding measures to improve the friction and wear properties of composites materials,and reducing the wear amount of composites 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 Fig.9.

For the ring-block friction and wear mode,due to its special contact mode,the actual contact area between the friction pair and the sample surface is small at the initial stage,and there is only a thin film because of physical adsorption on the contact surface.Under the action of external force,the contact micro bump is easy to destroy the physical adsorption film and enter the contact surface,and formed furrows on the surface under the action of friction.Friction heat is easily generated in the friction process,which increases the temperature of the contact surface.When the temperature rises,the exposed copper phase is prone to be oxidized by oxygen in the air,thus forming an oxide film on the contact surface,the oxide film with complete morphology is helpful to reduce the friction coefficient of the composites.At the same time,the exposed copper phase is softened and adhesive wear occurs as the surface temperature rises,and point pits tend to be formed on the surface.As the experiment continued,the copper phase on the surface was covered by oxide film and fine debris,which reduced the probability of oxidation wear and adhesive wear.Meanwhile,the graphite phase deformed under the action of cyclic stress,and finally fell off to form lamellar graphite,which was transferred to the surface of the sample and friction pair to form a friction film with high graphite content,and the friction coefficient of the composites is further reduced due to the self-lubricating effect of graphite.At the later stage of the friction experiment,the contact surface area increased and a complete friction film was gradually formed,and making the surface more flat.The copper phase almost did not contact directly,which reduced the oxidation wear and adhesive wear.The area around the hard micro-convex points was filled with fine debris,which increased the contact area and reduced the abrasive wear,so 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.

Conclusion

In order to analyze the tribological behavior of G/Cu and the CCG-G/Cu composites with different content of CCG more intuitively and systematically,the friction coefficient,wear rate and microstructure of composites after ring-block friction and wear experiment are characterized and analyzed,and the friction mechanisms at different stages are simulated and analyzed.The following conclusions are obtained:

(1)The addition of CCG can form a complete friction layer with higher graphite content on the contact surface more quickly,which can effectively improve tribological behavior of the composites.When the addition amount is 20wt%,the wear rate is the lowest(3.65×10^{-5} $mm^3/N.m$).When the additive amount is too high,the excessive friction film graphite will lead to the deepening of fatigue wear,the friction layer is prone to fall off,leading to an increase of wear rate.

(2)The micro-structure and micro-morphology characterized by SEM and TEM of composites after friction and wear experiment show that the friction surface structure is seriously damaged under the action of cyclic stress.the graphite layer spacing increased and interlayer shedding finally occurs under the action of friction,oxidation and plastic deformation occurs in the copper phase and a mass of deformation zones exists in the friction layer.The TEM images of the friction cross section show that deformation zone is mainly composed of accumulation zone,drag zone and carbon film.

(3)The initial stage of experiments is mainly dominated by abrasive wear and adhesive wear under the action of furrow and frictional heat,the exposed copper is oxidized by oxygen in the air and oxidative wear occurs when the temperature of the contact surface rises,and an incomplete oxide film is formed on the surface of the copper-rich area.Fatigue wear occurred mainly in the later stage,the graphite phase is exfoliated and transferred to the contact surface under cyclic stress,thus forming a complete friction film with high graphite content,which effectively reduces the friction coefficient of the composites.

Declarations

The authors declared that they have no conflicts of interest to this work.We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

Acknowledgements

The authors are appreciative to the State Key Laboratory for Powder Metallurgy Foundation at Central South University for the use of characterization equipment and facilities.

References

1. Tu, C.J., Chen, D., Chen, Z.H.,et al: Improving the Tribological Behavior of Graphite/Cu Matrix Self-Lubricating Composite Contact Strip by Electroplating Zn on Graphite[J]. Tribol. Lett. **31**(2), 91–98 (2008)
2. Moustafa, F., El-Badry, S.A., Sanad, A.M., et al. Friction and wear of copper–graphite composites made with Cu-coated and uncoated graphite powder[J]. Wear, 2002
3. SUN, Q., WANG, Z.: YIN B, et al. The tribological properties and wear mechanism of copper coated graphite doped Sialon ceramic composites at wide range temperature from 25 to 800°C [J]. Tribology International, 2018, 123(10 – 6
4. Cui, G., Niu, M., Zhu, S., et al: Dry-Sliding Tribological Properties of Bronze–Graphite Composites[J]. Tribol. Lett. **48**(2), 111–122 (2012)
5. Justyna Grzonka,Mirosław J.Kruszewski, Rosiński, M.,et al: Interfacial microstructure of copper/diamond composites fabricated via a powder metallurgical route[J]. Mater. Charact. **99**, 188–194 (2015)

6. GRZONKA, J., KRUSZEWSKI M J, R.O.S.I.ŃS.K.I.M., et al.: Interfacial microstructure of copper/diamond composites fabricated via a powder metallurgical route [J]. Materials Characterization, 2015, 99(188 – 94
7. KOV ČIK, J., EMMER, Š: BIELEK J. Thermal conductivity of Cu-graphite composites [J]. Int. J. Therm. Sci. **90**, 298–302 (2015)
8. GRANDIN, M.: WIKLUND U. Friction, wear and tribofilm formation on electrical contact materials in reciprocating sliding against silver-graphite [J]. Wear **302**(1–2), 1481–1491 (2013)
9. ZHU, L., YI, M., WANG, L., et al.: Effects of foam copper on the mechanical properties and tribological properties of graphite/copper composites [J]. Tribology International, 2020, 148(106164
10. PENG, X., HUANG, Y., HAN, X., et al.: High volume fraction of copper coated graphite flake\Nitrogen doped carbon fiber reinforced aluminum matrix composites [J]. Journal of Alloys and Compounds, 2020, 822(153584
11. RAN, L., PENG, K., YI, M., et al.: Ablation property of a C/C–Cu composite prepared by pressureless infiltration [J]. Mater. Lett. **65**(13), 2076–2078 (2011)
12. ZHU, J.M., LI J W, LIU, T., et al.: Differences in mechanical behaviors and characteristics between natural graphite/copper composites and carbon-coated graphite/copper composites [J]. Materials Characterization, 2020, 162(110195
13. KOU, G., GUO L-J, LI Z-Q, et al.: Microstructure and flexural properties of C/C-Cu composites strengthened with in-situ grown carbon nanotubes [J]. J. Alloy. Compd. **694**, 1054–1060 (2017)
14. BASHIR, B., SHAHEEN, W.: ASGHAR M, et al. Copper doped manganese ferrites nanoparticles anchored on graphene nano-sheets for high performance energy storage applications [J]. J. Alloy. Compd. **695**, 881–887 (2017)
15. LI, X., NATSUKI, J.: NATSUKI T. “Sandwich” copper nanoparticle @ graphene oxide composites: High-Temperature stability and long-term stable conductivity [J]. Materials Characterization, 2021, 110887
16. GAO, X., YUE, H.: GUO E, et al. Mechanical properties and thermal conductivity of graphene reinforced copper matrix composites [J]. Powder Technol. **301**, 601–607 (2016)
17. CHENG, J., GAN, X.: CHEN S, et al. Properties and microstructure of copper/nickel-iron-coated graphite composites prepared by electroless plating and spark plasma sintering [J]. Powder Technology, 2019, 343(705 – 13
18. CHEN, J., REN, S., HE, X., et al.: Properties and microstructure of nickel-coated graphite flakes/copper composites fabricated by spark plasma sintering [J]. Carbon **121**, 25–34 (2017)
19. WU, S., YI, M., GE, Y., et al.: Effect of carbon fiber reinforcement on the tribological performance and behavior of aircraft carbon brake discs [J]. Carbon, 2017, 117(279 – 92
20. CHEN G X, LI F X, D.O.N.G.L., et al.: Friction and wear behaviour of stainless steel rubbing against copper-impregnated metallized carbon [J]. Tribol. Int. **42**(6), 934–939 (2009)
21. CUI, G., BI, Q., ZHU, S., et al.: Tribological properties of bronze–graphite composites under sea water condition [J]. Tribol. Int. **53**, 76–86 (2012)

22. FAKIH, B., DIENWIEBEL, M.: The structure of tribolayers at the commutator and brush interface: A case study of failed and non-failed DC motors [J]. Tribology International, 2015, 92(21 – 8

Figures

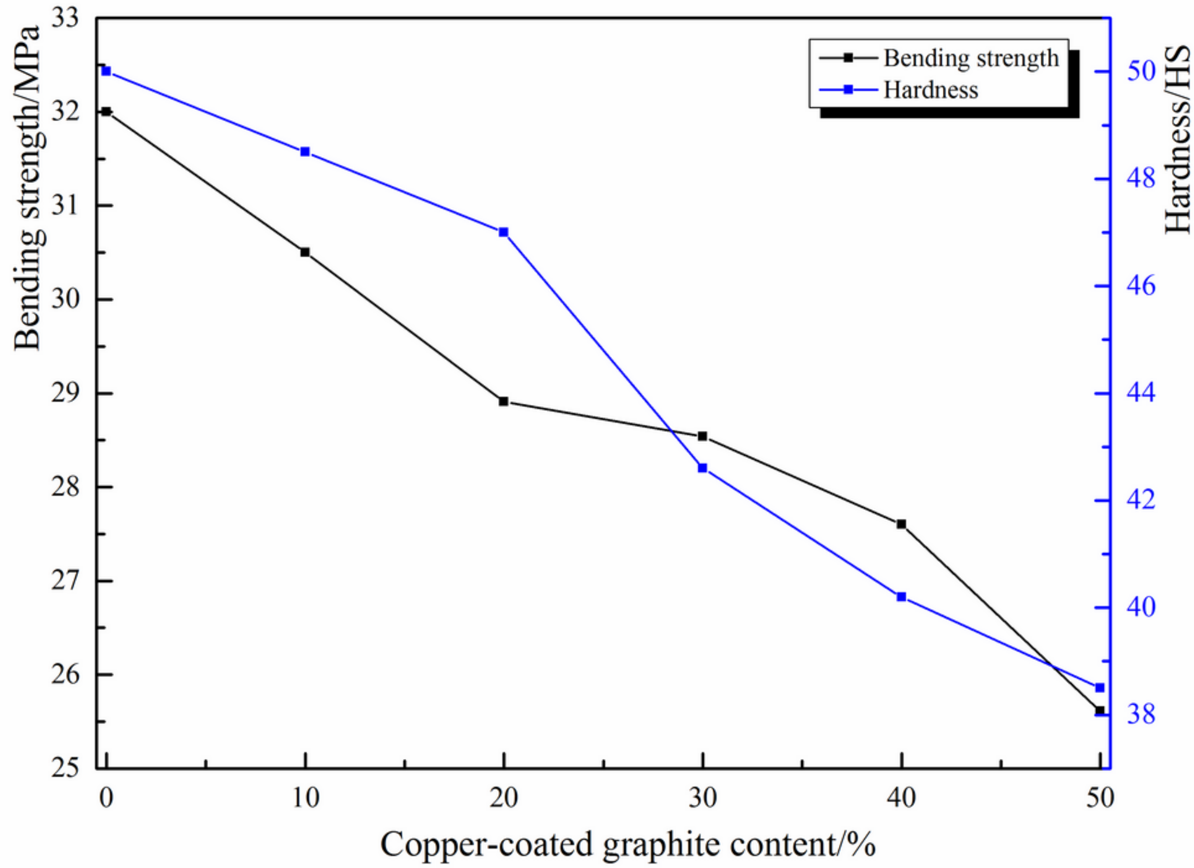

Figure 1

The mechanical properties of the G/Cu and CCG-G/Cu composites

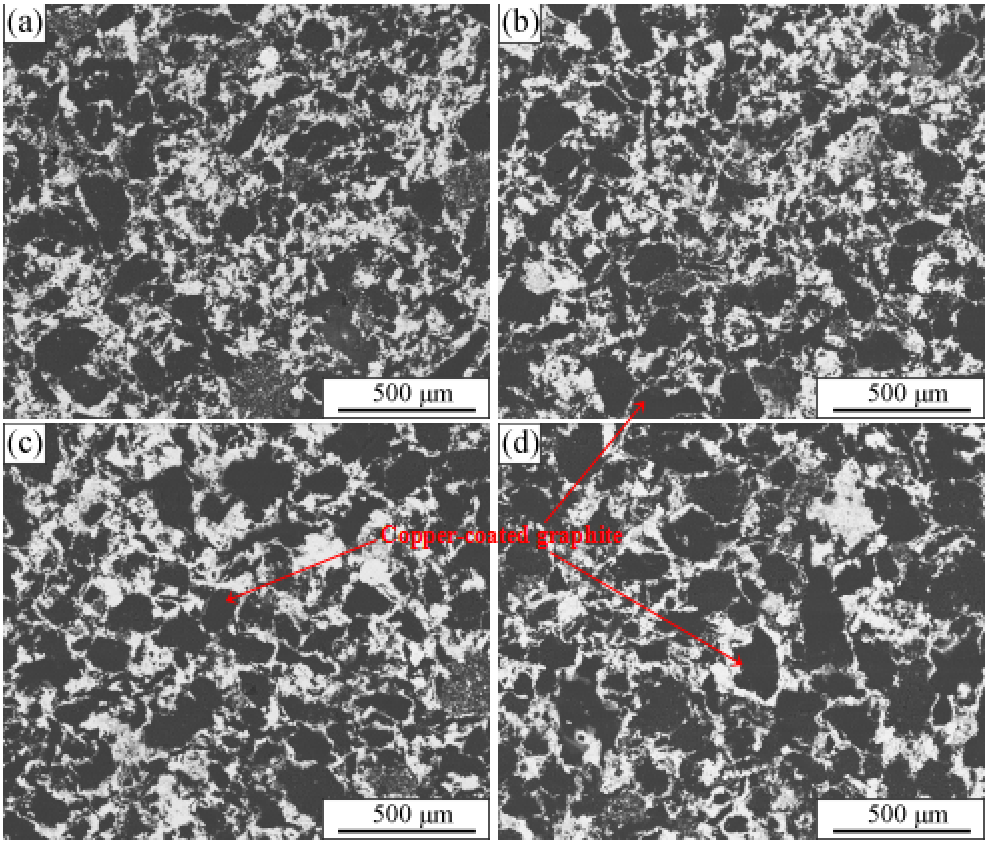

Figure 2

SEM micrograph of composites with CCG content of (a)0wt%,(b)20wt%,(c)30wt% and (d)50wt%

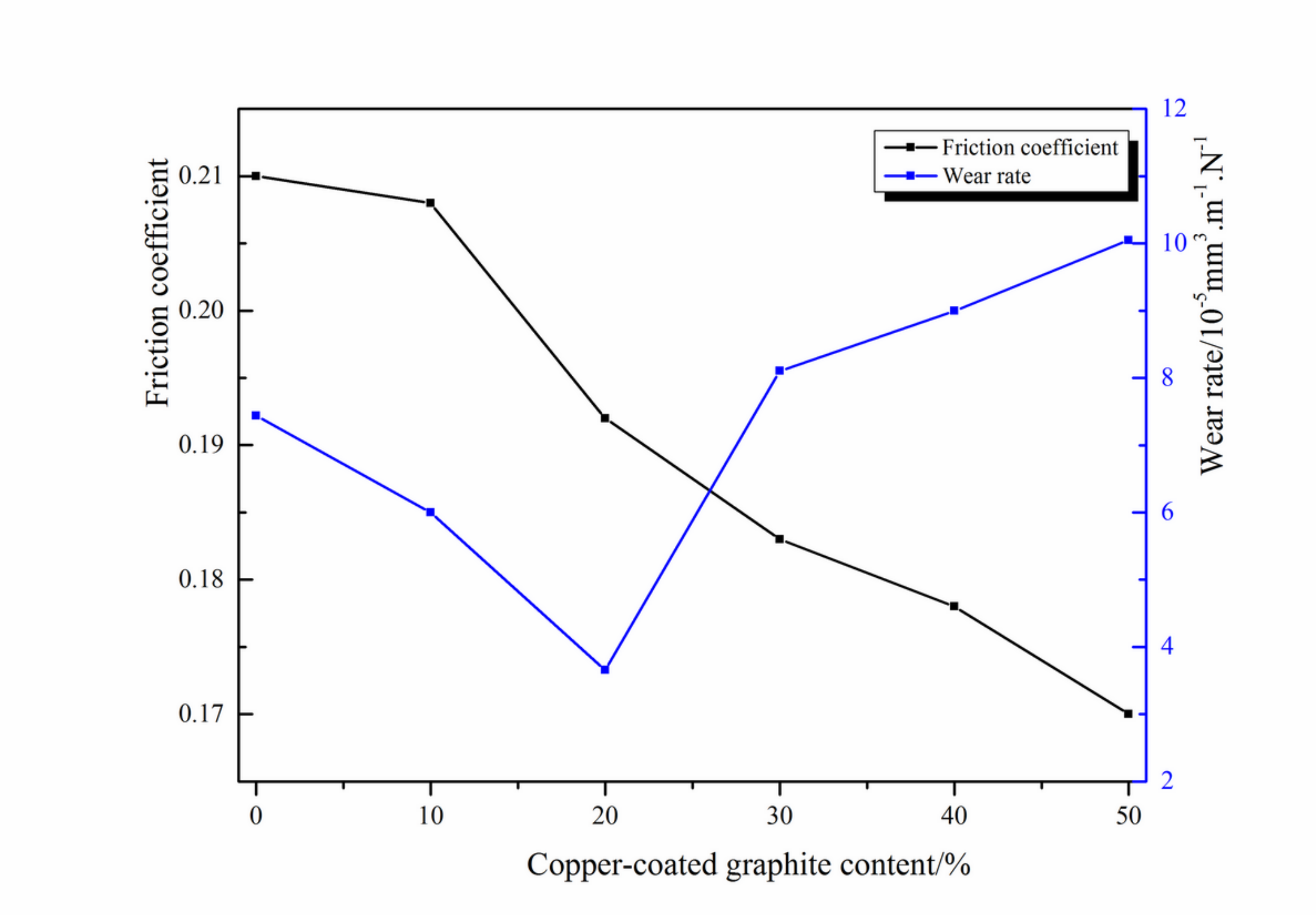

Figure 3

Tribological properties of the CCG-G/Cu composites with different CCG content

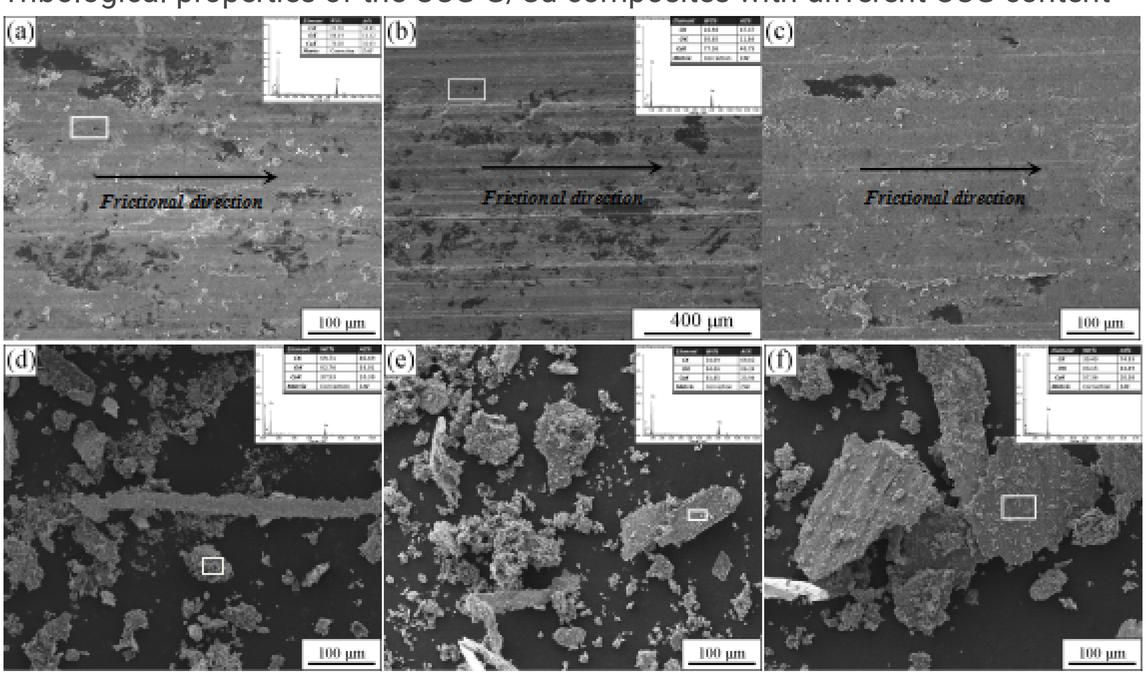

Figure 4

The SEM micrograms of the worn surface and debris:(a)(d)G/Cu composites,(b)(e)20wt%CCG-G/Cu composites and(c)(f)40wt%CCG-G/Cu composites

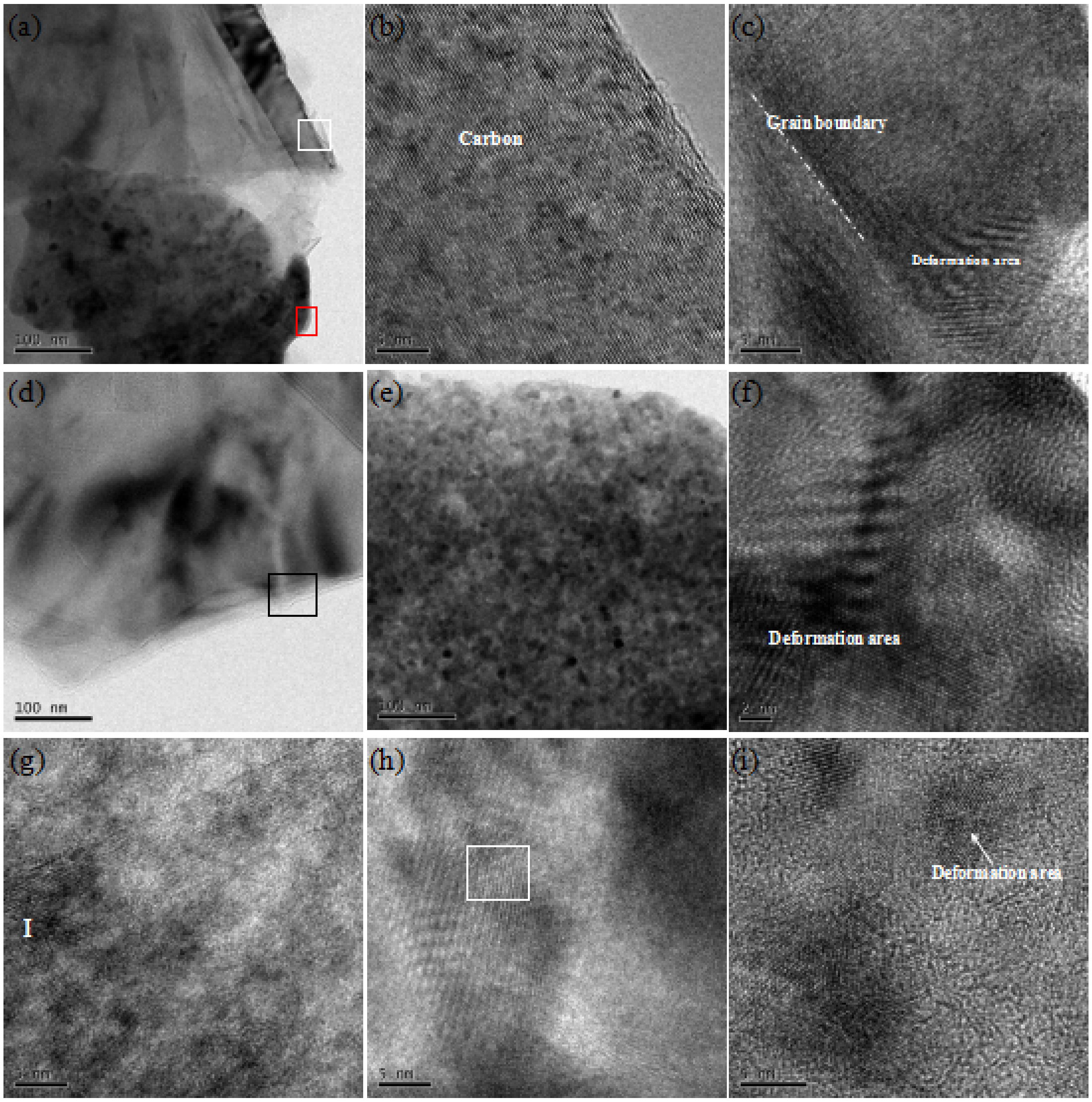

Figure 5

The TEM and HRTEM micrograms of debris:(a)morphology microgram of the G/Cu composites,(b)enlargement of the white box in Fig.5(a),(c)enlargement frame in Fig.5(a),(f)enlarged image of the deformation zone in Fig.5(c);(d)and(e)morphology image of the CCG-G/Cu composites,(g)enlargement of the box in Fig.5(d),(h)enlargement of the box in Fig.5(e) and (f)enlarged microgram of box area in Fig.5(e)

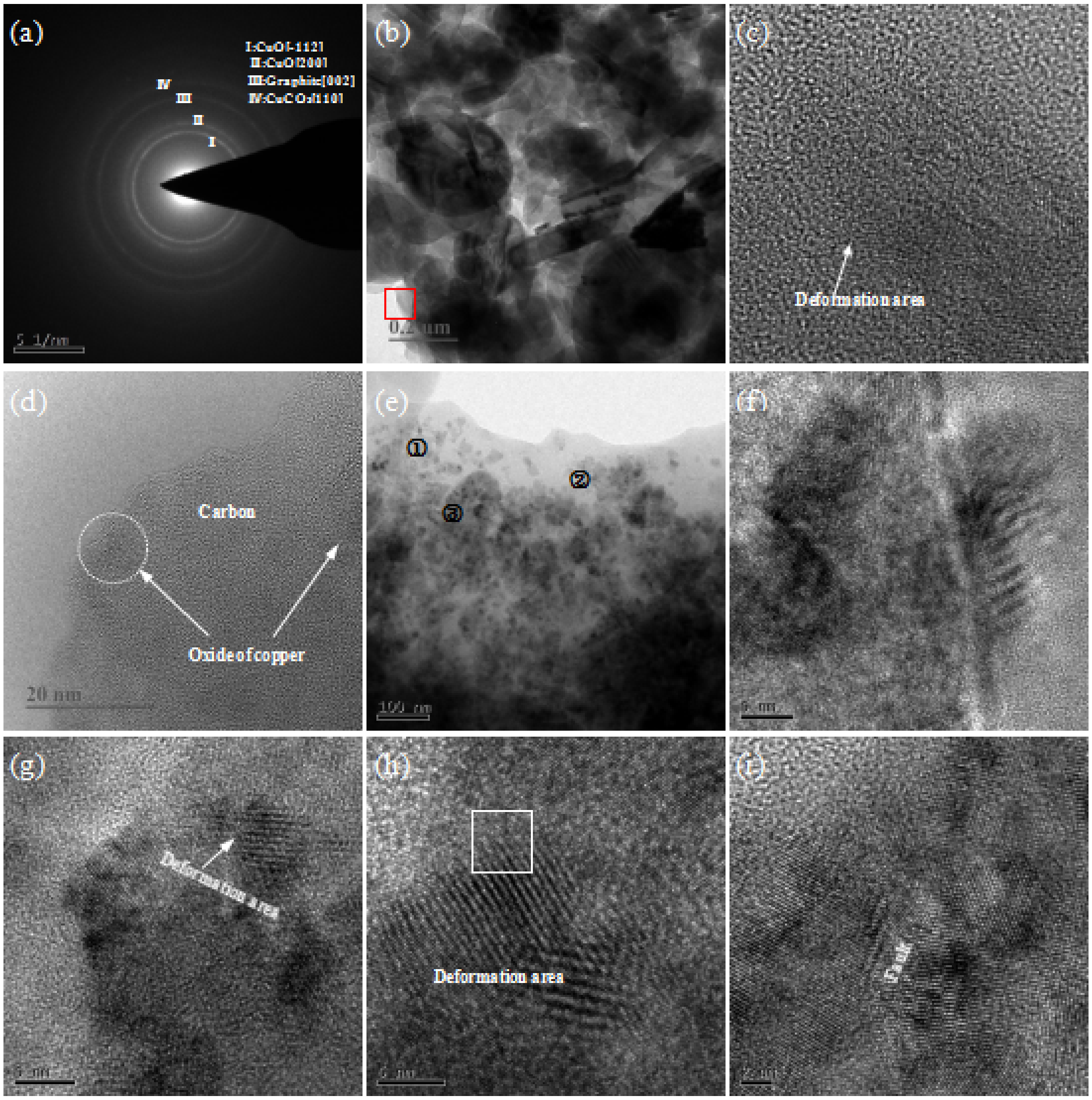

Figure 6

SAED spectra(a),TEM microgram of the G/Cu composites(b) and 20wt%CCG-G/Cu composites(e), (c~d)HRTEM micrograms of the frame in Fig.6(b),(e)HRTEM microgram of the box area in Fig.5(d) and (f)enlarged microgram of area in Fig.6(e)

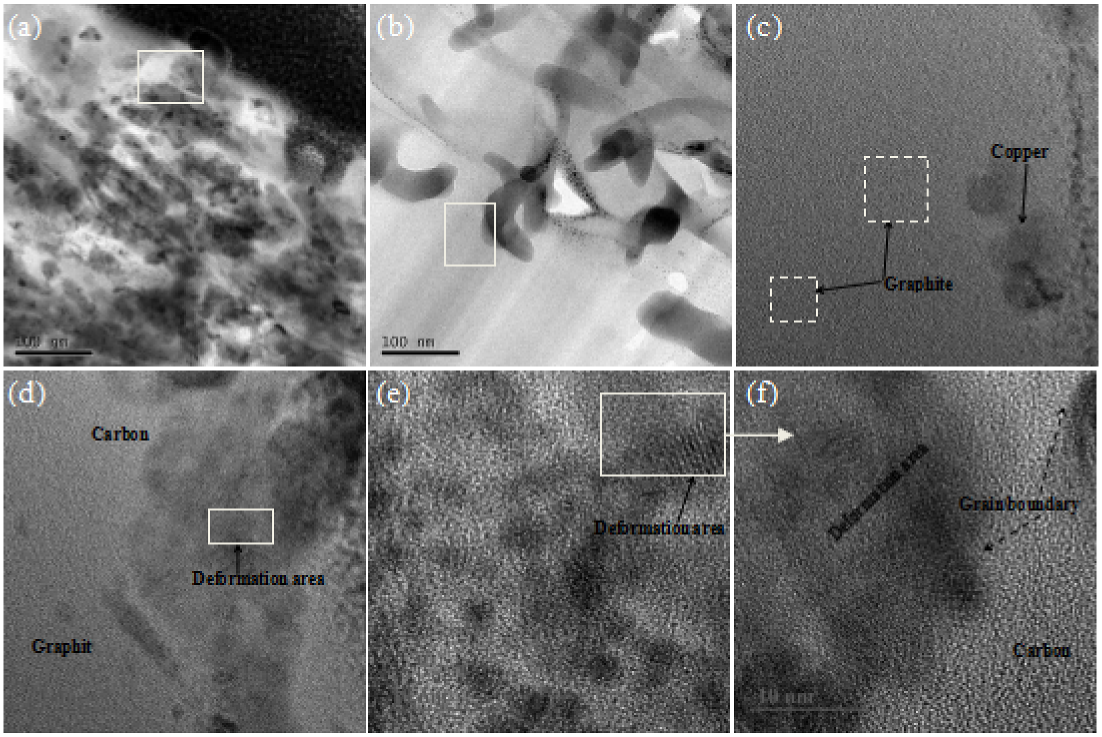

Figure 7

The TEM and HRTEM micrograms of friction cross section of the G/Cu composites(a)morphology images in deformation zone,(b)morphology images in matrix,(c)HRTEM images in matrix,(d)HRTEM images in deformation zone,(e)enlargement of local view in Fig.7(d)and(f)enlargement of local view in Fig.7(e)

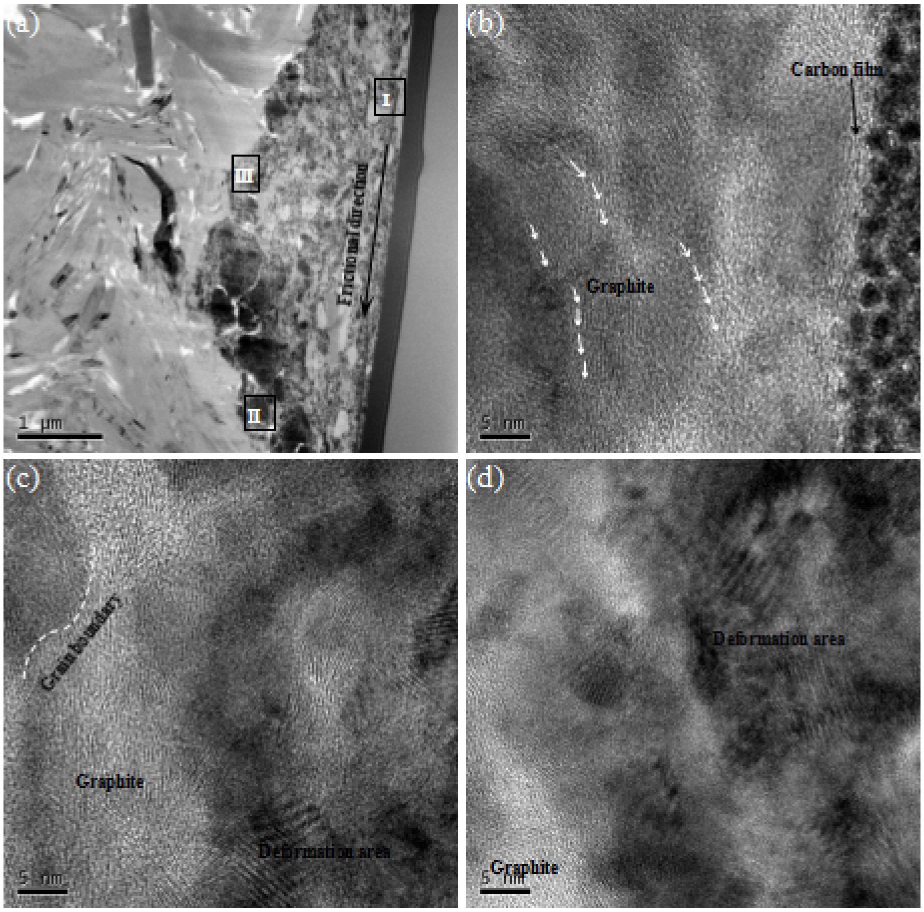

Figure 8

(a)TEM microgram,(b)HRTEM image of area I in Fig.8(a),(c)HRTEM microgram of area□and (d)HRTEM microgram of area□ of friction cross section of 20wt%CCG-G/Cu composites

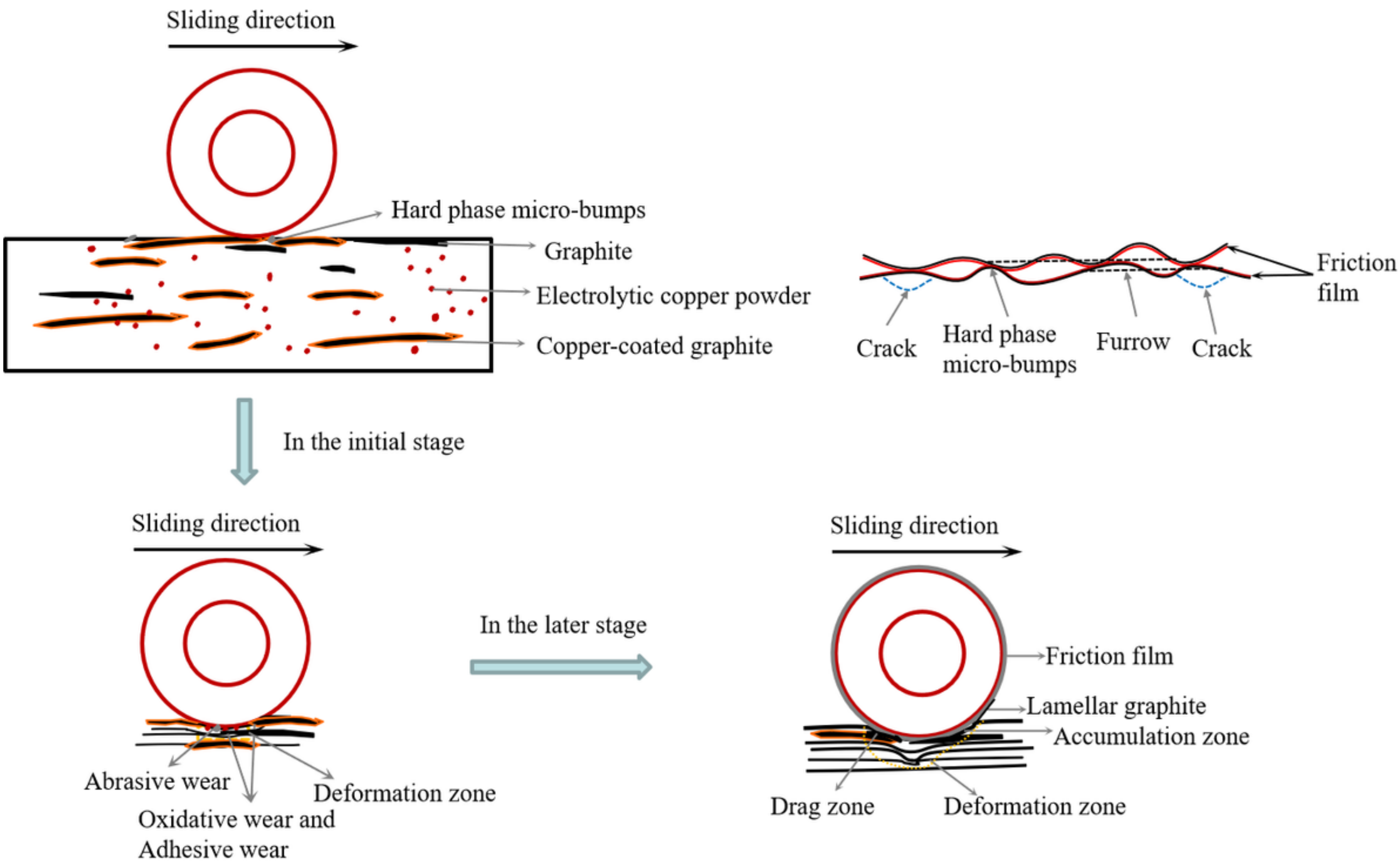

Figure 9

Schematic diagram of friction mechanism