



Effect of tungsten carbide particles on microstructure and mechanical properties of Cu alloy composite bit matrix

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Abstract

Copper alloy composite bit matrix was prepared by pressureless vacuum infiltration, using at least one of the three kinds of tungsten carbide particles, for example, irregular cast tungsten carbide, monocrystalline tungsten carbide and sintered reduced tungsten carbide particles. The effects of powder particle morphology, particle size and mass fraction of tungsten carbide on the microstructure and mechanical properties of copper alloy composite were investigated by means of scanning electron microscopy, X-ray diffraction and abrasive wear test in detail. The results show that tungsten carbide morphology and particle size have obvious effects on the mechanical properties of copper alloy composites. Cast tungsten carbide partially dissolved in the copper alloy binding phase, and layers of $\text{Cu}_{0.3}\text{W}_{0.5}\text{Ni}_{0.1}\text{Mn}_{0.1}\text{C}$ phase with a thickness of around 8–15 μm were formed on the edge of the cast tungsten carbide. When 45% irregular crushed fine cast tungsten carbide and 15% monocrystalline cast tungsten carbide were used as the skeleton, satisfactory comprehensive performance of the reinforced copper alloy composite bit matrix was obtained, with the bending strength, impact toughness and hardness reaching 1048 MPa, 4.95 J/cm² and 43.6 HRC, respectively. The main wear mechanism was that the tungsten carbide particles firstly protruded from the friction surface after the copper alloy matrix was worn, and then peeled off from the matrix when further wear occurred.

Keywords Polycrystalline diamond compact · Pressureless vacuum infiltration · Copper alloy composite bit matrix · Microstructure characterization · Abrasive wear behavior

1 Introduction

Polycrystalline diamond compact (PDC) bit has been widely used in the field of oil and gas exploration due to the improved efficiency and the reduced costs. PDC bit has

gradually replaced the roller cone bit as the main rock breaking [1, 2]. PDC bit included PDC cutters and composite bit matrix, and PDC cutters were brazed to the matrix. The bit matrix including Ni-based, Fe-based and Cu alloy-based composite materials was primarily used to bond the skeleton hard phase, for example, WC, TiC and TiB [3]. In the process of PDC bit manufacturing by pressureless infiltration, the key factor that directly determined the performance of PDC bit matrix was the composition of matrix powder and sintering impregnation process. Different types of tungsten carbides such as cast tungsten carbide, sintered tungsten carbide and monocrystalline tungsten carbide powders were added to enhance the comprehensive performance of the bit matrix [4]. At present, the most widely used framework strengthening phase was cast tungsten carbide, or monocrystalline tungsten carbide, which can effectively increase the wear resistance and erosion resistance of the matrix material. In particular, cast tungsten carbide was a

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eutectic product of WC and W_2C phases, which have the advantages of high hardness (2100–3100 HV), high thermal stability, high wear resistance and good wettability with metal, and were widely reinforced to metal materials to improve wear resistance [5].

In the process of oil and gas exploration, PDC bit needs to bear various complicated working conditions in the bottom hole [4]. With the increasing requirements of drilling conditions, it was inevitable to further improve the mechanical properties of Cu alloy composite PDC bit matrix. Most PDC bits were made of cast tungsten carbide particles as skeleton powder, which was formed by pressureless infiltration of Cu alloy composite PDC bit matrix with low melting point [6]. Therefore, performance of the composite bit matrix was required to include wear resistance, erosion resistance, impact toughness, hardness, bending strength, linear expansion coefficient and density [7, 8]. Some composite bit matrix consisting of a steel-based body was difficult to adapt to harsh drilling environments for its relatively poor wear resistance and their performance reached the upper mechanical and economic limitations. As a binding phase metal, Cu alloy has good compatibility with the skeleton material and excellent wetting characteristic and binding strength, which can form a good interface binding between the matrix and the reinforcing phase and avoid the high-temperature graphitization of diamond [9, 10]. The hardness and wear resistance of Cu alloy composite PDC bit matrix were the key to the performance of material when tungsten carbide skeleton phase was prepared by the method of pressureless infiltration of low-melting-point Cu alloy [11].

Although a lot of research work has been reported in recent years concerning on improving the properties of matrix materials by adding tungsten carbide particles, there are few systematic reports on the reinforcement of copper alloy composite PDC bit matrix by different cast tungsten carbide particles. In present work, tungsten carbide particles with different morphologies and sizes were utilized to reinforce the Cu alloy composite PDC bit matrix by pressureless infiltration process. The microstructure, hardness, impact toughness, fracture toughness and wear resistance of Cu alloy composite PDC bit matrix were analyzed and discussed. The effects of powder particle morphology, particle size and mass fraction of tungsten carbide on the microstructure and mechanical properties of Cu alloy composite PDC bit matrix were investigated. The wear mechanism of Cu alloy composite PDC bit matrix was revealed, and the effect of composite strengthening on friction and wear of copper alloy composite bit matrix was further described.

2 Experimental material and procedures

2.1 Raw materials and methods

Figure 1 exhibits the images of tungsten carbide powders and Cu alloy-based powder. Table 1 lists the particle sizes (F_{ss} , μm) and chemical composition of the raw powders used in this research. The tungsten carbide had three types: irregular crushed cast tungsten carbide powder (YZ) in Fig. 1a, monocrystalline cast tungsten carbide (YJ) in Fig. 1b and sintered reduced tungsten carbide (YK) in Fig. 1c. Cu alloy-based composite powder ($\leq 120 \mu\text{m}$ powder) was CuNiZnMn alloy, and the mass percentage of each component was 52.26% Cu, 15.68% Ni, 8.22% Zn and 23.77% Mn, with allowances for other elements. Specimens of Cu alloy composite PDC bit matrix were designated with the tungsten carbide reinforcement as listed in Table 2, which were named as specimens Nos. 1–4. In each group of specimens, the total mass content of the hard phase was 60%, and the mass content of copper alloy composite powder as binding phase was 40%.

2.2 Specimen preparation and infiltration process

Figure 2 shows the schematic diagram of the pressureless infiltration process for preparing the Cu alloy composite PDC bit matrix. The specific experimental process could be described as follows: (1) Preparation of skeleton powder: skeleton powder was composed of tungsten carbide powder, and the skeleton powder was mixed evenly by V-type powder mixer at a speed of 40–50 r/min and mixing time of 240 min. (2) Mold loading: the tungsten carbide powder forming the skeleton was initially placed at the bottom of the cylindrical graphite crucible into the graphite mold (the inner cavity size of the mold was 55 mm in diameter and 120 mm in height), and then, the Cu alloy-based powder as the bond metal was poured in and vibrated gently as shown in Fig. 2. The specimen number and skeleton powder formula are given in Table 2. (3) Infiltration process: the graphite crucible was put into the vacuum heat treatment furnace, and the specimen was impregnated. The temperature of infiltration was less than 1180 °C, the holding time during the infiltration process was at least 60 min and the vacuum degree was held below 10 Pa during the whole heating and insulation. After the infiltration process, the cylindrical graphite crucible should be cooled to room temperature and removed from the heat treatment furnace, and then, the relevant specimens were cut for testing in detail.

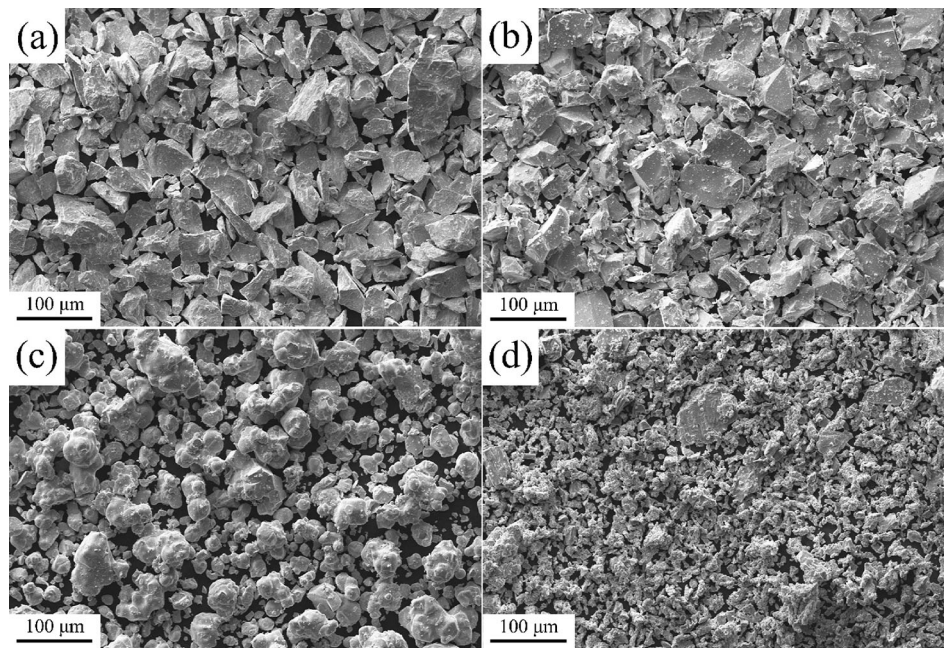


Fig. 1 Images of morphology of raw tungsten carbide powders and copper alloy-based powder. **a** YZ; **b** YJ; **c** YK; **d** Cu alloy-based powder

Table 1 Particle sizes and chemical composition of raw powders used in this work

Powder	Fsss/ μm	Chemical composition/wt. %			
		W	C _{total}	C _{free}	O
YZC	150	≥ 93.65	5.82	0.04	0.37
YZF	45	≥ 93.59	5.87	0.04	0.44
YJ	150	≥ 93.71	5.85	0.08	0.35
TK	25	≥ 93.75	6.14	0.02	0.03

YZC—Irregular crushed coarse cast tungsten carbide; YZF—Irregular crushed fine cast tungsten carbide; C_{total}—total C content in WC; C_{free}—free C content in WC

Table 2 Composition of prepared Cu alloy composite PDC bit matrix

Specimen No.	Skeleton powder	Cu alloy-based powder
1	60 wt.% YZC	40 wt.%
2	60 wt.% YJ	40 wt.%
3	45 wt.% YZF + 15 wt.% YJ	40 wt.%
4	45 wt.% YZC + 15 wt.% YK	40 wt.%

2.3 Experimental methods

The particle size of the experimental raw material was determined by MS2000 Hydro2000MU laser particle size meter. The microstructures of polished specimens were observed by scanning electron microscopy (SEM, BRUKER TESCAN-3, German) coupled with energy-dispersive

spectrum (EDS) under the secondary electron (SE) mode. The statistical data of grains in this article were obtained, and the average values of the 5–6 pictures and Image J software were used as data analysis and processing software, respectively. By utilizing Cu K α radiation with a step rate of 0.02 ($^{\circ}$)/s, the phases of specimens were characterized by X-ray diffraction (XRD, BRUKER D2 PHASER RAX-30). By employing MDI JADE (Edition 6.5, Materials Data Ltd., America), the XRD patterns were numerically analyzed. Utilizing three-point bend test, the transverse-rupture strength (TRS) was determined at room temperature with a span length of 14.5 mm at a loading velocity of 0.5 mm/min utilizing material test machine (Shimadzu WE-100). TRS values were calculated based on the standard BS EN ISO 3327-2009. Hardness was calculated using a Vickers diamond pyramid indenter (HV30, FV-800, Japan) with a pressure of 300 N and a dwell time

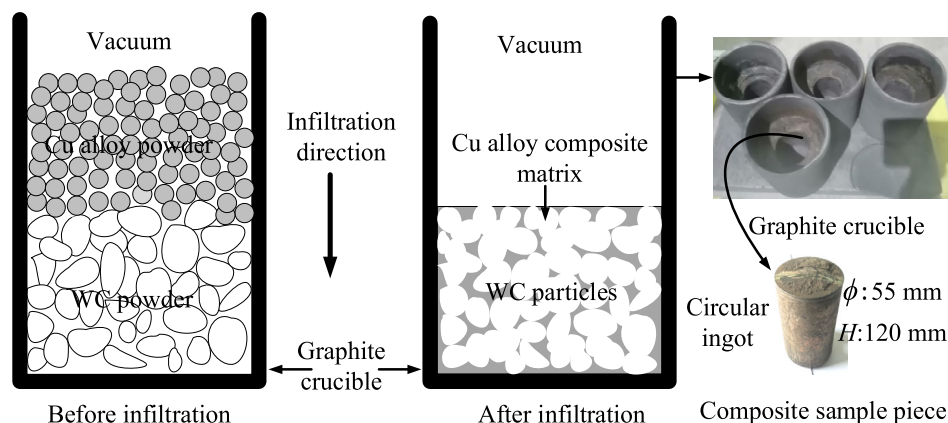


Fig. 2 Schematic diagram of pressureless infiltration process for manufacture of Cu alloy composite PDC bit matrix. ϕ —Diameter of ingot; H —height of ingot

of 15 s. Impact toughness mainly represents the total energy consumed during crack formation and propagation. The impact toughness of copper alloy composite bit matrix was measured by CSC-1101 impact testing machine. The specimen size for impact toughness test was $50 \text{ mm} \times 5 \text{ mm} \times 5 \text{ mm}$ and test samples followed standard GB/T 1817-2017. The impact fracture surface was observed by SEM under SE mode. All mechanical properties data in this work were obtained, and the average values of the 5–7 experimental consequences were calculated. Furthermore, the specimen was subjected to wear test by MFT-EC8000 friction-wear platform. The size of the specimen was $15 \text{ mm} \times 15 \text{ mm} \times 6 \text{ mm}$, and the loadings were 20 and 40 N. Under the loading condition, 20 N was used to represent the wear condition under conventional load, and 40 N was used to study the wear mechanism of the bit under relatively heavy load. The distance of reciprocating wear was 6 mm, the frequency was 2 Hz and the loading wear time was 60 min. The SiC ball with diameter of 4 mm was selected after the contrast experiment of friction pair of Si_3N_4 and SiC. Bruker GT-X probe surface profiler was used to measure the 3D profile of the worn surface and the wear surface morphology of the specimen. In order to ensure the accuracy and reliability of the results, 2D wear section detection was shown as the dashed line in the middle of the scratch.

3 Results and discussion

3.1 Microstructure and phase composition

Figure 3 shows SEM micrographs of tungsten carbide particles reinforced Cu alloy composite PDC bit matrix at different magnifications of observation. As shown in Fig. 3a, d, g, j, the tungsten carbide particles in all specimens were

distributed uniformly throughout the specimen without significant clustering or isolation, which were closely bonded with the Cu alloy-based binding phase. Moreover, there was little change in tungsten carbide particle size. The overall grains of specimens Nos. 3 and 4 were significantly smaller and more uniform than those of specimens Nos. 1 and 2. As can be seen from Fig. 3b, e, h, k, pores can be seen at sharp corners of tungsten carbide particles reinforced Cu alloy composite by crushed cast tungsten carbide particles in Fig. 3b, e, h. However, in specimen No. 3, the number of pores has been significantly reduced, and there was much fine tungsten carbide diffusely distributed and also no obvious pores existed in specimen No. 4 as shown in Fig. 3c, f, i. The main reason was that tungsten carbide particles were irregular, which was caused by the uneven porosity of the skeleton and the blocking of some binding phase channels of infiltration. Furthermore, the two distinct phases had clearly shown fairly pronounced diffusion layer structure with a thickness of 8–15 μm around the edge of cast tungsten carbide particles, which indicated that tungsten carbide was locally dissolved in the copper alloy matrix, as shown in A interface in Fig. 3b, e, h, k. The diffusion layer on the surface of tungsten carbide particles was conducive to the formation of a good combination of cast tungsten carbide and impregnated alloy in the copper alloy bit matrix and to improving the bonding force between tungsten carbide and the matrix and its strengthening effect on the matrix, which was conducive to the improvement of the properties of copper alloy matrix materials. Moreover, when monocrystalline cast tungsten carbide powder and sintered tungsten carbide powder were added individually, no diffusion layer structure appeared at the edge of tungsten carbide particles, as shown in B interface and C interface in Fig. 3b, e, h, k.

Figure 4 shows the grains size distribution map of specimens Nos. 1–4. Remarkably, the grain size distribution of specimens Nos. 1 and 2 was unimodal, and the

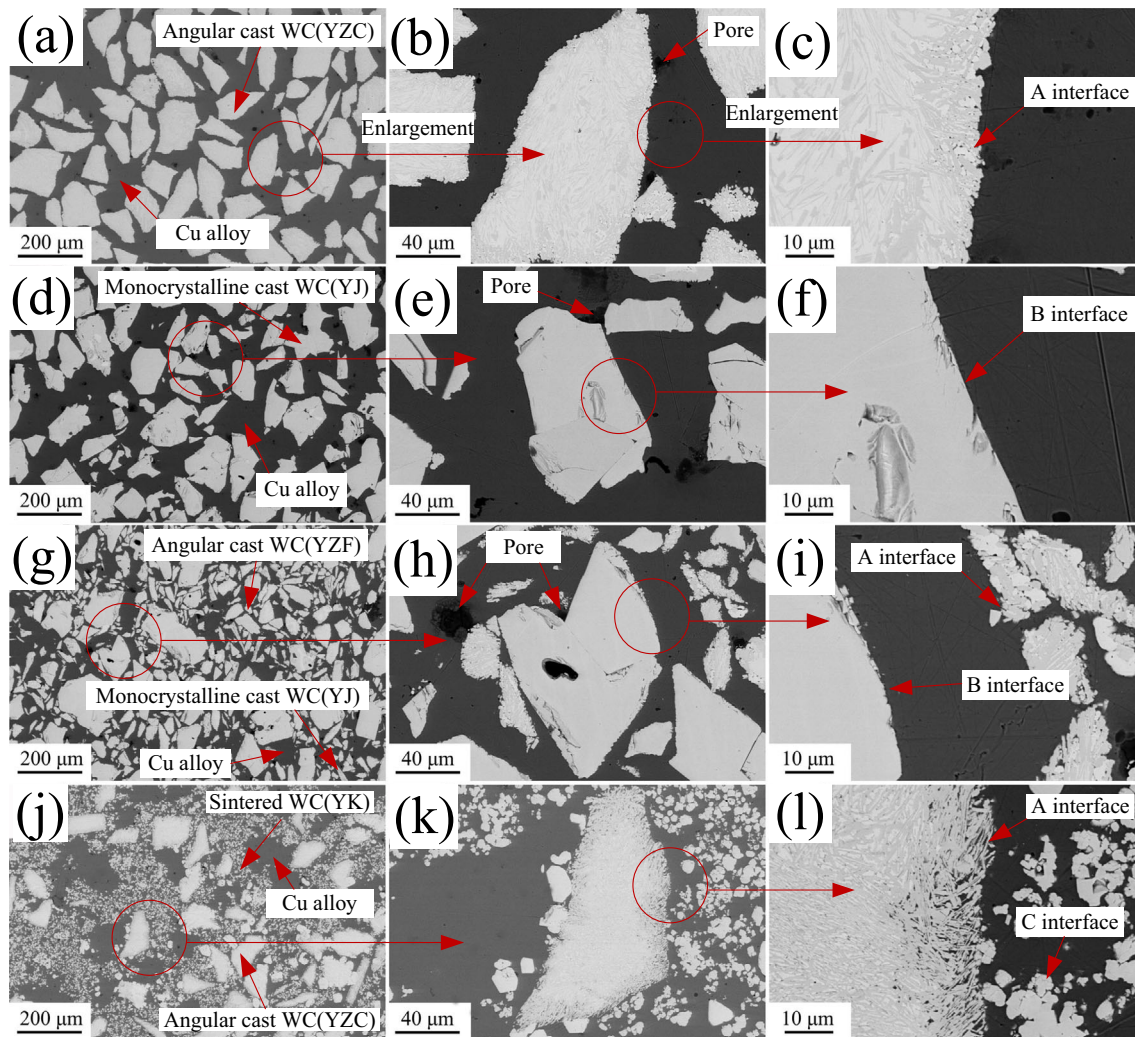


Fig. 3 SEM micrographs of tungsten carbide particles reinforced Cu alloy composite bit matrix at different magnifications. **a, b, c** Specimen No. 1; **d, e, f** specimen No. 2; **g, h, i** specimen No. 3; **j, k, l** specimen No. 4

grains distribution was mainly between 100 and 150 μm as shown in Fig. 4a, b, while the grains distribution of specimens Nos. 3 and 4 was obviously bimodal as shown in Fig. 4c, d. The finer angular cast tungsten carbide (45% YZF, Fss of 45 μm) powder was added to specimen No. 3 and finer sintered tungsten carbide powder (15% YK, Fss of 25 μm) was added to specimen No. 4. Grains distribution of specimen No. 3 was mainly between 25–50 and 100–150 μm . In specimen No. 4, the fine WC grains smaller than 25 μm accounted for 85%. However, the fine WC grains in specimen No. 3 were more evenly distributed in the copper alloy matrix, while the fine grains of the specimen No. 4 were dispersively distributed, but there was more copper alloy pools phenomenon after infiltration.

Figure 5 shows the scanning diagram of element distribution of tungsten carbide particles reinforced copper alloy composite bit matrix. From the scanning results of all specimen surfaces, it can be seen that the hard phase

tungsten carbide forms a clear skeleton structure, and the Cu alloy elements form a binding phase. (Elements of Ni, Mn and Zn have similar laws as Cu, so that only Cu was listed for analysis in the paper.) As can be clearly seen from Fig. 5, the skeleton of tungsten carbide particles becomes more compact by adding finer irregular cast tungsten carbide powder (45% YZF, Fss of 45 μm) and finer sintered tungsten carbide powder (15% YK, Fss of 25 μm). The results indicated that local dissolution of tungsten carbide occurs in Cu alloy composite bit matrix. The diffusion elements of W, Cu and Ni along the interface were smooth and continuous, indicating that no inter-metallic compounds are formed on the interface between tungsten carbide particles and Cu alloy composite bit matrix. In addition, elements Ni, Mn and Zn were evenly distributed in the Cu alloy composite matrix, indicating that elements Ni, Mn and Zn have been fully fused with the impregnated Cu alloy as the binding phase of tungsten

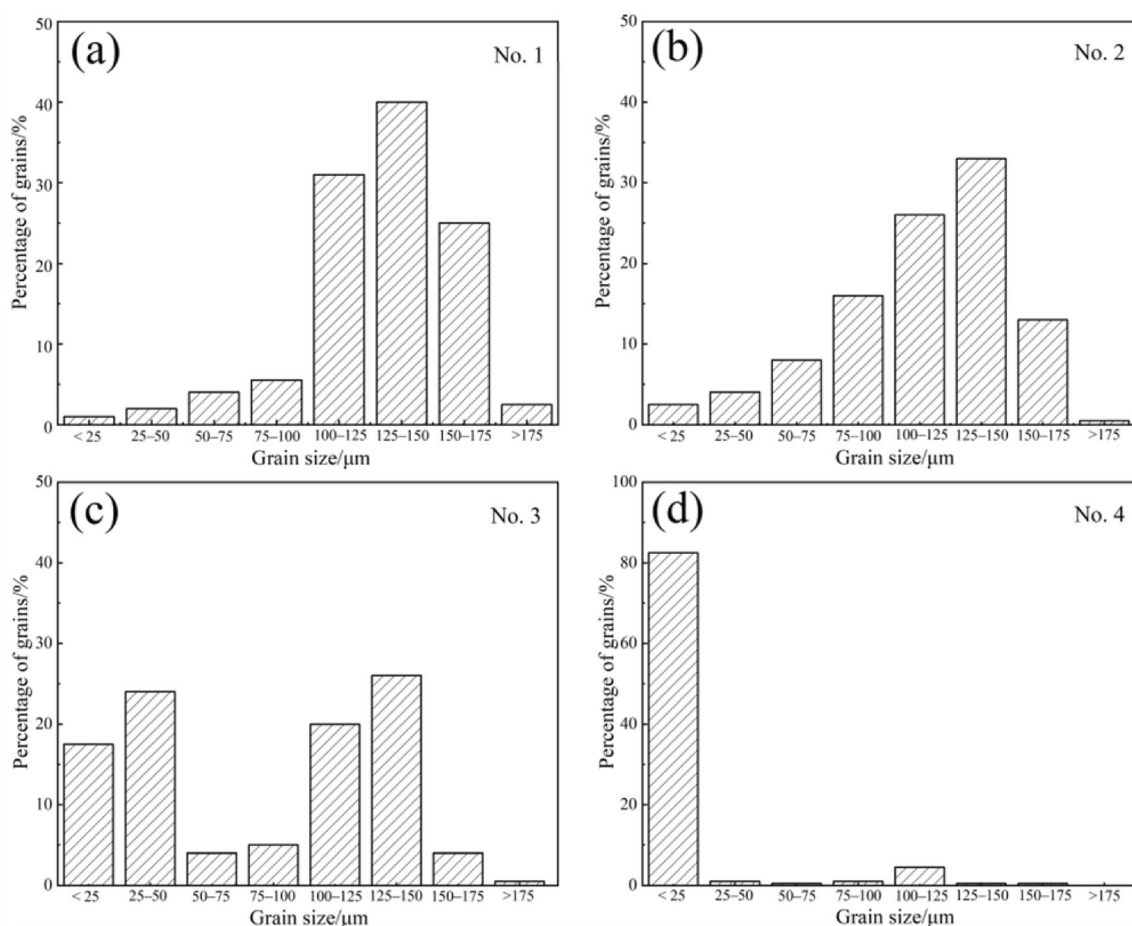


Fig. 4 Grains size distribution map of specimens No. 1 (a), No. 2 (b), No. 3 (c) and No. 4 (d)

carbide. The diffusion layer was beneficial to the formation of good bonding between tungsten carbide and impregnated alloy in the matrix, improving the bonding force between tungsten carbide and matrix and its strengthening effect on matrix [12, 13].

Figure 6 shows the XRD patterns of tungsten carbide particles reinforced Cu alloy composite PDC bit matrix of specimens Nos. 1–4. The phases of WC, W_2C and $Cu_{0.5}Ni_{0.3}Zn_{0.1}Mn_{0.1}$ were obvious to be observed in the specimens Nos. 1–4. After adding tungsten carbide reinforcement phase to Cu alloy composite PDC bit matrix, it can be inferred that $Cu_{0.5}Ni_{0.3}Zn_{0.1}Mn_{0.1}$ was the Cu alloy matrix phase, while WC and W_2C phases should be derived from tungsten carbide particles. Elements W, Cu, Ni and Mn were diffused along the interface, and intermetallic compounds $Cu_{0.3}W_{0.5}Ni_{0.1}Mn_{0.1}C$ were formed on the interface by the reaction of W and C elements of tungsten carbide powder and Cu alloy-based powder after melting at high temperature in specimens Nos. 1, 3 and 4. Among them, adding irregular crushed cast tungsten carbide in specimen No. 1 resulted in the most developed diffusion layer, and the XRD peak is more obvious as

shown in Fig. 6. Through adding irregular crushed fine cast tungsten carbide in specimen No. 3 or reducing the content of coarse cast tungsten carbide particles in specimen No. 4, the XRD peak existed and was weaker than that in specimen No. 1, which was mainly due to the formation of diffusible layers at grain boundaries of tungsten carbide particles. This finding was consistent with the conclusion that the boundary of tungsten carbide particles formed the A interface and C interface diffusion layer in Fig. 3.

3.2 Mechanical properties

Table 3 lists the mechanical properties of Cu alloy composite PDC bit matrix of specimens Nos. 1–4. The mechanical properties of prepared specimens have met the criteria of the polycrystalline diamond bit matrix (SY/T 5217-2000 standard, bending strength ≥ 530 MPa, impact toughness ≥ 2 J/cm²). Wear resistance was a major technical index to evaluate the performance of Cu alloy composite PDC bit matrix. The higher the hardness of the material was, the better its wear resistance was, which determines directly the selection of the bit as well as the

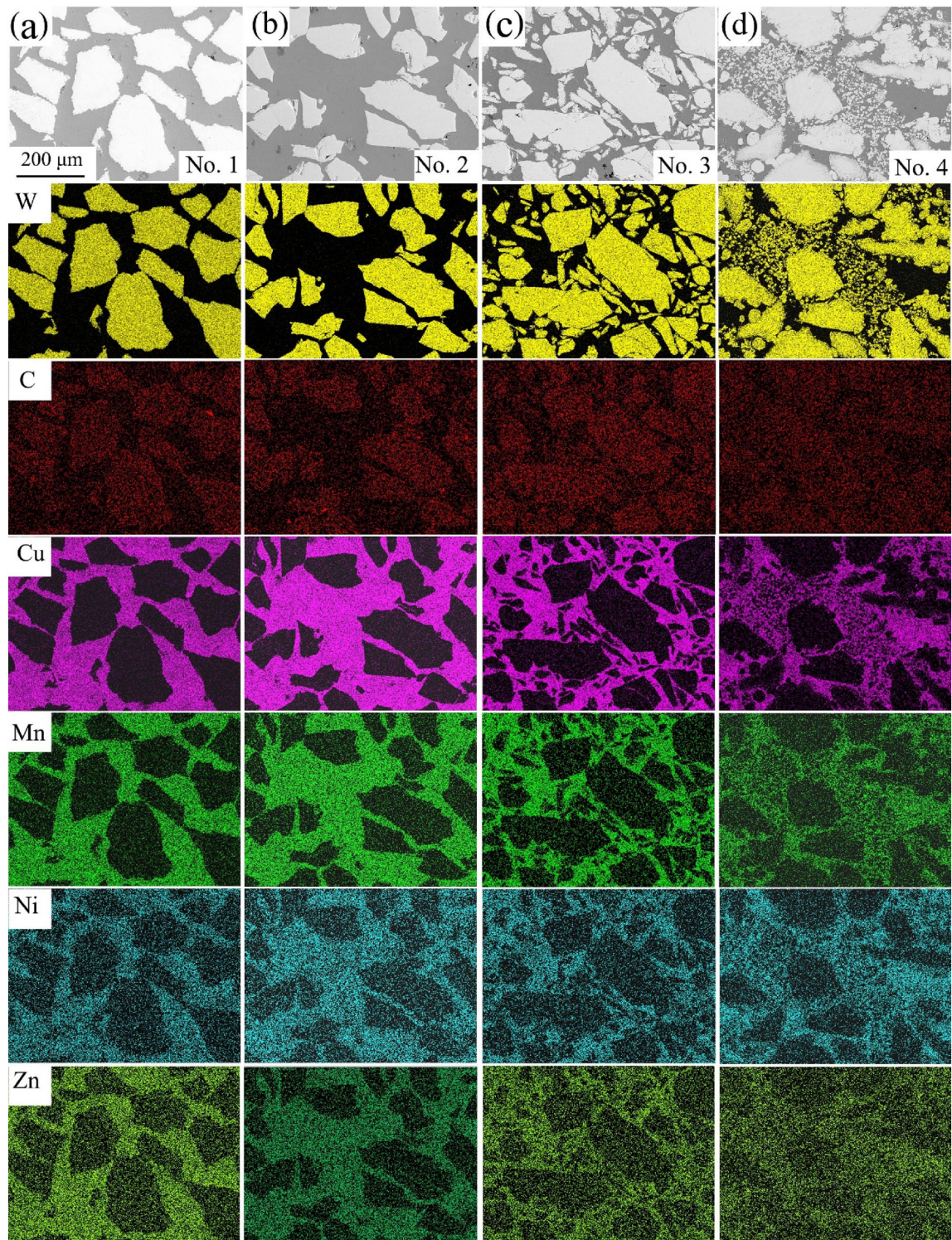


Fig. 5 Scanning diagram of element distribution of WC particles reinforced Cu alloy composite bit matrix of specimens No. 1 (a), No. 2 (b), No. 3 (c) and No. 4 (d)

drilling procedure parameters and the improvement of drilling engineering technical index. Depending on the testing results in Table 3, the Rockwell hardness measurement values of the prepared Cu alloy composite PDC

bit matrix were between 24.9 and 43.6 HRC. When the same mass fraction of tungsten carbide was used in the skeleton powder of specimens Nos. 1 and 2, the hardness of the specimen No. 1 prepared by crushed tungsten carbide

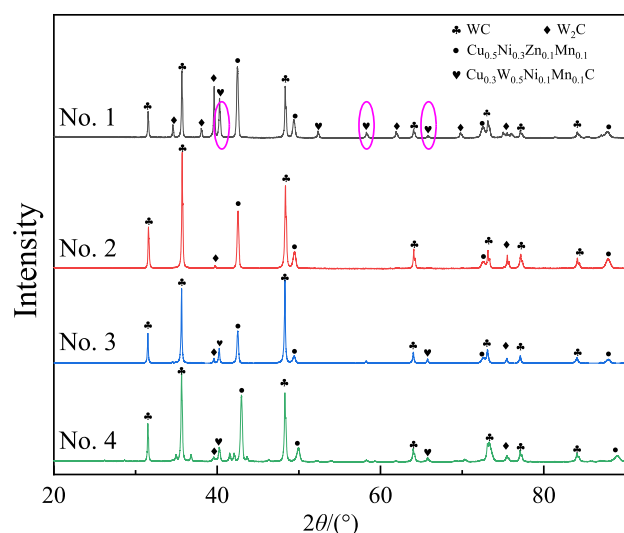


Fig. 6 XRD patterns of WC particles reinforced Cu alloy composite bit matrix of specimens Nos. 1–4

Table 3 Mechanical properties of Cu alloy composite PDC bit matrix of specimens Nos. 1–4

Specimen	Hardness/ HRC	Bending strength/ MPa	Impact toughness/(J cm ⁻²)
No. 1	29.2	756	2.96
No. 2	24.9	820	3.54
No. 3	43.6	1048	4.95
No. 4	38.2	940	4.37

powder was slightly higher than that of specimen No. 2 prepared by monocrystalline tungsten carbide powder. This was primarily attributed to the fact that the hardness of cast tungsten carbide powder was 2200–2400 HV_{0.1}, while that of monocrystalline tungsten carbide powder was 1600–1800 HV_{0.1}. On the other hand, specimen No. 3 adding the finer irregular cast tungsten carbide powder (45% YZF, Fss of 45 μm) and specimen No. 4 adding the finer sintered WC powder (15% YK, Fss of 25 μm) reduced the particle size of tungsten carbide powder, and the hardness of Cu alloy composite PDC bit matrix generally increased with Rockwell hardness values of 43.6 and 38.2 HRC, respectively.

As for the bending strength of the bit matrix material, it can be seen from Table 3 that the bending strength of specimens Nos. 1 and 2 was comparable. However, adding the fine tungsten carbide has an obvious effect on the bending strength of the Cu alloy composite PDC bit matrix. The bending strength of specimens Nos. 3 and 4 was much higher than that of specimens Nos. 1 and 2. The specimen No. 3 adding the finer angular cast tungsten carbide (45% YZF, Fss of 45 μm) powder has the highest bending

strength, which was 1048 MPa. The reasons were as follows: the strength of Cu alloy composite PDC bit matrix was mainly dominated by the tungsten carbide skeleton, and the interface formed between the Cu alloy matrix phase and the sharp angle of broken tungsten carbide particles was prone to stress concentration and crack initiation, leading to premature failure of the matrix. Fine-grained tungsten carbide particles were more conducive to hindering crack propagation and promoting crack deflection. In addition to the formation of diffusible layer between cast tungsten carbide and Cu alloy, fine tungsten carbide also played a role in dispersively strengthening the matrix phase of Cu alloy [14, 15]. This was consistent with the view that coarse tungsten carbide grains have high toughness and resistance to crack propagation, while fine tungsten carbide grains compensate for wear losses by strengthening metal binders [16, 17].

It can also be seen from Table 3 that the impact toughness values of specimens Nos. 3 and 4 were higher than those of single tungsten carbide in specimens Nos. 1 and 2. The impact toughness of specimens Nos. 3 and 4 prepared by adding fine-grained tungsten carbide was higher than that of specimens Nos. 1 and 2 prepared by crushed tungsten carbide. Figure 7 shows the impact fracture of tungsten carbide particles reinforced Cu alloy composite PDC bit matrix specimens Nos. 1–4. As can be seen from Fig. 7, the binding phase of the matrix was fully wrapped on the tungsten carbide. In the fracture morphology of the specimen, pores can be seen, and there are many pits generated by the stripping of tungsten carbide. It was obvious that most tungsten carbide particles had cleavage fracture, and the fracture was typically brittle cleavage fracture. The fracture process of the matrix was mainly dominated by the cleavage fracture of tungsten carbide particles, and the cleavage cracks converged rapidly, leading to the final failure of the material and the low fracture toughness of the material. Therefore, the impact toughness of the material was low, and its value ranged from 2.96 to 4.95 J/cm². The average impact value of specimen No. 3 was up to 4.95 J/cm². The binding phase of specimens was also fully wrapped around the tungsten carbide, and most of the tungsten carbides at the fracture junction were brittle cleavage fracture, which was combined with part of the dimple fracture of the binding phase [18]. When the tungsten carbide particles became smaller, the tungsten carbide particles played a role in retarding the crack propagation and deflating the crack. At the same time, due to the fine particles, the binding phase was more fully wrapped with hard tungsten carbide particles, and the crack propagation path increased, so that the crack was easy to expand in the matrix, namely the binding phase, and the impact toughness increased [19]. The coarse WC grains resulted in high toughness and resistance to crack

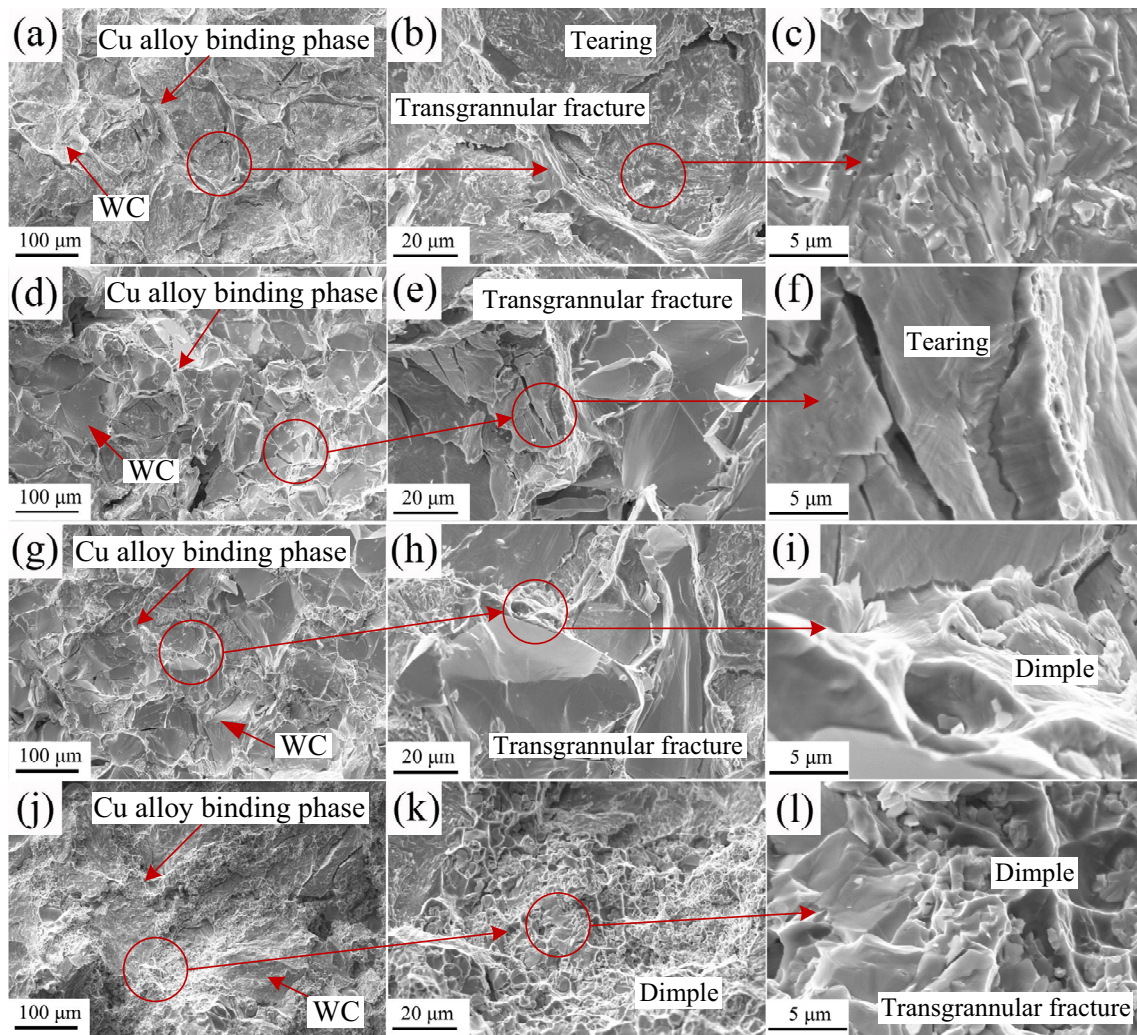


Fig. 7 Impact fracture morphologies of tungsten carbide particles reinforced Cu alloy composite PDC bit matrix of specimens No. 1 (a, b, c), No. 2 (d, e, f), No. 3 (g, h, i) and No. 4 (j, k, l)

propagation [20], while fine WC grains compensated wear resistance loss by reinforcing the metallic binder [8]. In this manner, accurate control of WC grain size can successfully facilitate the wear resistance and toughness of cemented carbide. Based on the analysis of the grains size distribution map in Fig. 4, it can be seen that the comprehensive properties of the dual scale structure cemented carbides prepared in this study are more advantageous in the specimen No. 3. The fine WC grains in specimen No. 3 were more evenly distributed in the copper alloy matrix, while those of the specimen No. 4 were also evenly distributed, but there was more copper alloy pools phenomenon after infiltration. Compared to the uniform structure, hardness, bending strength and impact toughness of specimen No. 3 in this study were greatly improved with the value reaching 43.6 HRC, 1048 MPa and 4.95 J/cm², respectively.

3.3 Wear resistance

Figure 8 shows the schematic of friction and wear experiment. The macroscopic scratch morphology of the four kinds of Cu alloy composite bit matrix specimens Nos. 1–4 at 60 min of wear is shown in Fig. 8.

After the loading wear experiment, the variation curve of friction coefficient with time in the wear process of Cu alloy composite PDC bit matrix can be obtained, as shown in Fig. 9. According to Fig. 9, the friction coefficient curve could be divided into three stages. During the initial stage I of wear, tungsten carbide particles in the matrix and Cu alloy matrix were simultaneously worn by abrasive. After 5–10 min, the friction coefficient of the four matrix materials basically remained stable. The main reason was that the actual contact area of the friction pair was very small at the beginning of the contact, which caused rapid

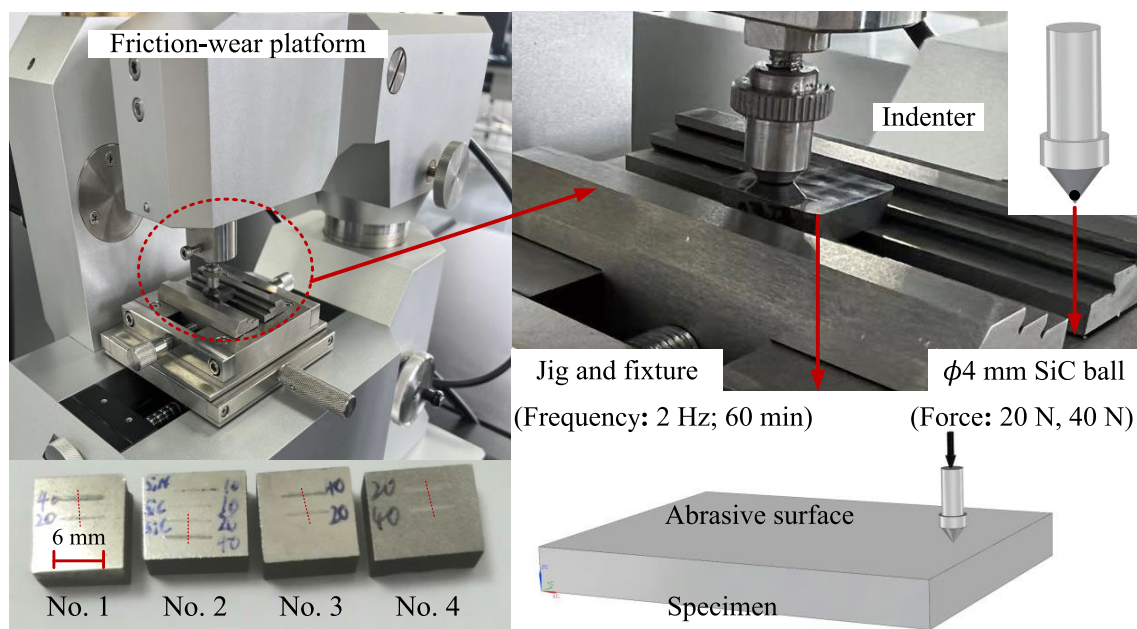


Fig. 8 Schematic of friction and wear experiment

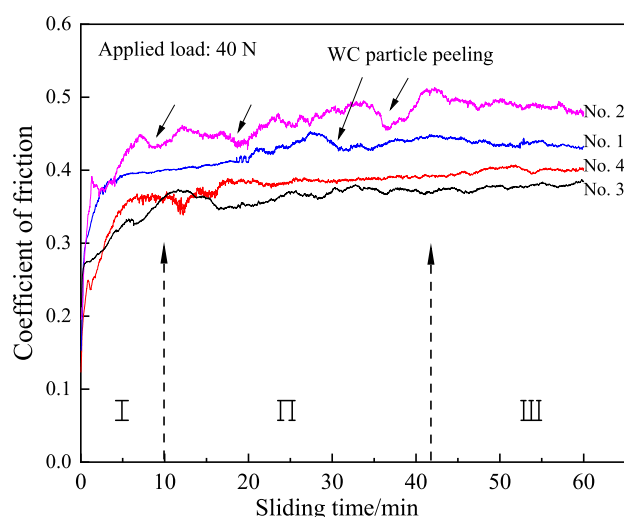


Fig. 9 Plot of variation in coefficient of friction with increasing sliding time at load of 40 N

wear immediately under the load. After a certain time of running in, the surface gradually ground flat, and then the actual contact area gradually increased and gradually transitioned to a normal and stable wear stage [8]. In stage II, under the abrasive wear condition, the Cu alloy matrix was heavily worn and concave, while the tungsten carbide particles were protruding above the matrix. As WC particles were pulled out, indentations or pits were formed on the surface of the matrix, and the friction coefficient decreased rapidly as shown in Fig. 9. The main reason was that the hard phase particles fell off and the matrix was severely worn, and the particle falling off would lead to the

sharp fluctuation of the wear rate curve. And the wear mechanism was mainly micro-cutting, particle falling off and brittle spalling [4, 10, 21]. In the late wear stage III, with the continuous concaving of Cu alloy matrix around the tungsten carbide particles, the supporting effect of matrix on the tungsten carbide particles decreased obviously, while some tungsten carbide particles were broken or broken and spalled under the action of abrasive continuous cutting and fatigue wear. The primary reason should be that some reinforced tungsten carbide particles could not sustain but eventually fractured and fragmented after the cyclic repetitions of loading and unloading during the sliding contact. The broken tungsten carbide particles and the copper alloy matrix “recovered” to the same level, the above wear process was repeated until the tungsten carbide particles were broken again, and the friction coefficient at this stage was basically stable [22, 23]. During the steady state, the average friction coefficient value for the four specimens Nos. 1–4 was about 0.43, 0.48, 0.34 and 0.38, respectively.

Figure 10 shows 3D wear topography and 2D wear section of tungsten carbide particles reinforced Cu alloy composite bit matrix specimens No. 1 (Fig. 10a), No. 2 (Fig. 10b), No. 3 (Fig. 10c) and No. 4 (Fig. 10d) by loading 20 and 40 N. Figure 10 shows that the wear on the surface of tungsten carbide particles position were higher than that on the Cu alloy substrate plane by loading 20 and 40 N and after 60 min reciprocating abrasive wear. This indicated that the copper alloy matrix would be worn by abrasive particles first during the wear process, and when the Cu alloy matrix was worn to a certain extent, the raised

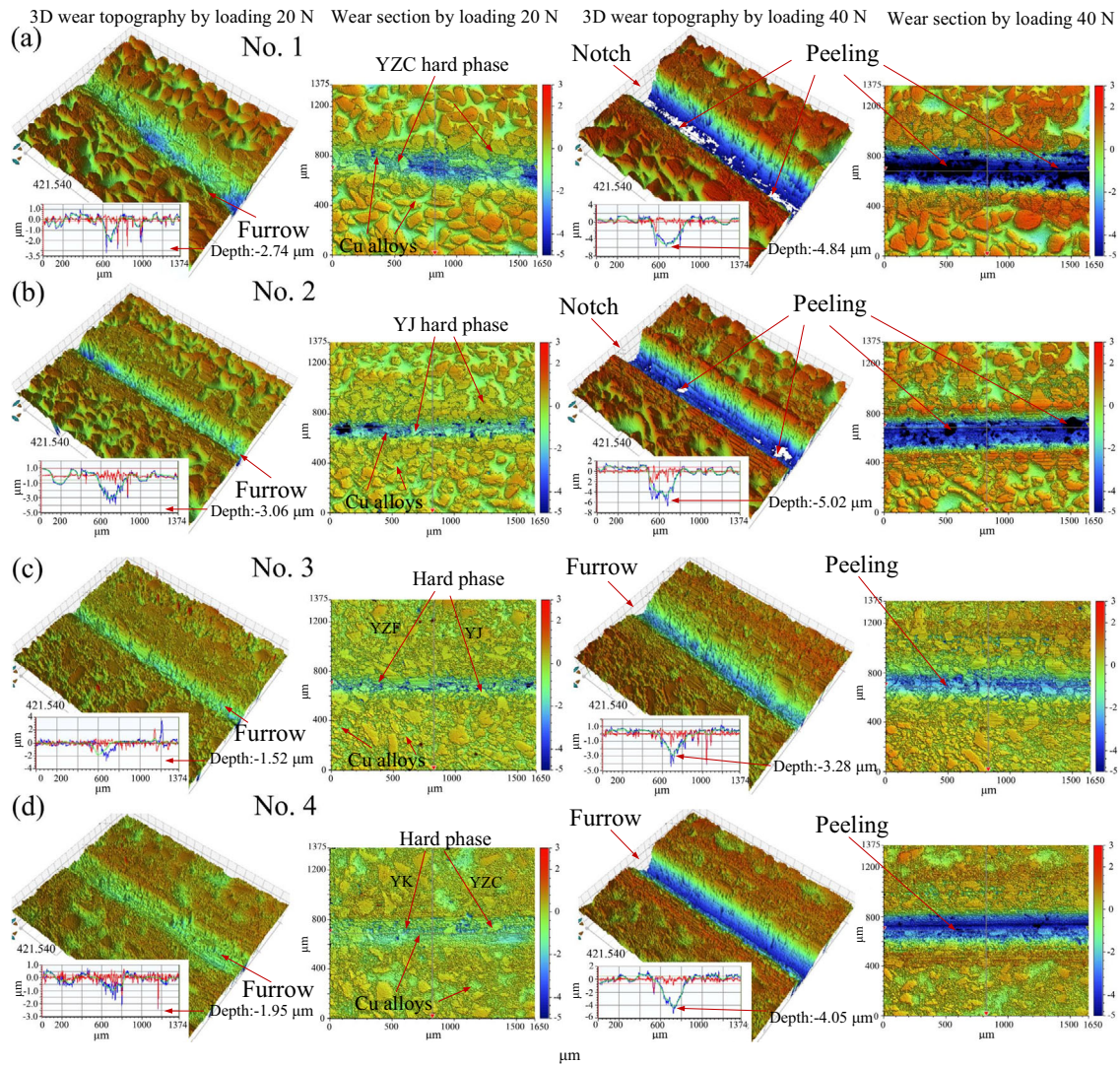


Fig. 10 3D wear topography and 2D wear section of tungsten carbide particles reinforced Cu alloy composite bit matrix of specimens No. 1 (a), No. 2 (b), No. 3 (c) and No. 4 (d) with load of 20 and 40 N

tungsten carbide particles protected the matrix from further wear, and the tungsten carbide particles bore abrasive wear. When 20 N was loaded, by comparing the micro wear morphology of matrix material specimens Nos. 1–4, it was found that the wear surface of the Cu matrix material was relatively flat and the furrow of Cu alloy matrix appeared, and the hard phase fell off less. Moreover, a part of Cu alloy matrix was “covered” in the surface of tungsten carbide particles, its wear contour is illustrated in Fig. 10 and the depth was measured 2.74, 3.06, 1.52 and 1.95 μm , respectively. When 40 N was loaded, the contour depth of specimens Nos. 1–4 was 4.84, 5.02, 3.28 and 4.05 μm , respectively.

The coarse particles crushed and monocrystalline tungsten carbide particles as the strengthening phase of Cu alloy matrix were used in specimens Nos. 1 and 2, which have relatively weak supporting effect on the matrix when

strengthening the Cu alloy matrix and are easy to crack or peel off from the matrix during the wear process. The deeper furrow was formed on the surface of friction damage. Moreover, holes on the surface of copper alloy matrix produced by exfoliated tungsten carbide particles are presented in Fig. 10. However, due to the addition of small tungsten carbide particles in specimens Nos. 3 and 4, which could be diffusely distributed in the Cu alloy matrix, the surface sliding friction coefficient of specimens No. 3 and No. 4 was small during the abrasive wear process, and only some small tungsten carbide particles fell off, which were not easy to be broken or spalled off from the matrix. Therefore, the Cu alloy bit matrix could be wear-resistant and effective after the addition of fine tungsten carbide particles. Furthermore, wear properties of Cu alloy bit matrix specimens Nos. 3 and 4 were significantly improved.

4 Conclusions

1. Tungsten carbide particles reinforced Cu alloy composite bit matrix, and the Cu alloy as the binding phase could be completely wrapped with tungsten carbide skeleton. Microstructural analysis revealed a uniform distribution of tungsten particles in the Cu alloy matrix with no cracks or delamination at the interface between the particles and matrix, indicating good bonding between the matrix and reinforcement. The diffusion layer structure with a thickness of 8–15 μm around the edge of cast tungsten carbide particles was pronounced.
2. Compared with coarser grain tungsten carbide, the Cu alloy composite bit matrix reinforced with some fine tungsten carbide could significantly improve the wear performance of Cu alloy composite bit matrix with fewer internal microcracks and no stress concentration. The hardness, bending strength and impact toughness of the finer angular cast tungsten carbide powder (45% YZF, Fss of 45 μm) specimen No. 3 reached 43.6 HRC, 1048 MPa and 4.95 J/cm², respectively.
3. The major wear mechanism was considered to be ploughing wear in Cu alloy matrix and fracture/fragmentation of tungsten carbide particles. The wear surface of copper alloy matrix of bit reinforced by irregular crushed cast tungsten carbide particles was flat, showing a large number of furrows of Cu alloy composite bit matrix, and irregular tungsten carbide particles were worn and became smooth. However, the tungsten carbide particles were prominent on the wear surface of the Cu alloy composite bit matrix reinforced by fine tungsten carbide particles, and a small number of tungsten carbide particles were broken or fractured.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have an influence on the work reported in this paper.

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