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Effect of nickel-plated graphite on microstructure and properties of matrix for Fe-based diamond tools

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Abstract: Nickel-plated graphite particles and unmodified graphite particles with different contents were added to the Fe-based diamond composites. The basic properties of those specimens were measured, including relative density, hardness, bending strength, abrasion ratio and holding force coefficient. And also, SEM, XRD and EDS were used to carry out microstructure characterization, phase analysis and element distribution of these specimens. The results show that nickel plating effectively improves the surface wettability of graphite particles. And it is determined that an element diffusion zone is formed on the transition interface between the nickel-plated graphite and the matrix materials, effectively enhancing the interfacial bonding strength. Also, the pores and cracks in the matrix generated by adding the graphite particles are reduced after nickel plating. Thus, the loss of basic properties of the specimens is restrained. But it is found the higher the graphite content is, the weaker the positive effect of nickel plating is. In addition, it is revealed that nickel plating plays a conducive part in the formation of graphite lubricants on the working surface, and nickel-plated graphites can slow down the thermal corrosion of the diamond particles inside the high-temperature sintered specimens.

Key words: diamond composites; nickel-plated graphite; microstructure; mechanical properties; lubrication mechanism

1 Introduction

Nowadays, the requirements for comprehensive performance of diamond tools are getting higher and higher [1−4]. Although the traditional Fe-based diamond tools have been widely applied, their working performance and applicability in different working environments have always been hotspots [5,6]. Many researchers have tried to add unconventional elements to the matrix of diamond tools to reduce their wear resistance, thereby further improving the working efficiency of diamond tools [7,8]. Graphite particles are also considered. The basic principle of adding graphite is to weaken the matrix performance [7−9], thus improving the exposure height of diamond particles at the outer edge of the matrix. This is conducive to increasing the self-sharpening ability of the matrix. And also, the working efficiency of the diamond tool can be improved. In addition, graphite inside the diamond tool matrix can also play a solid lubricant role with good thermal conductivity [10]. That is to say, during the working process, graphite lubricating films can be generated on the working surface of the tool, which can spread the heat caused by friction [7]. Also, those films can act as a collision buffer layer to improve the utilization of diamond particles. However, the addition of unmodified graphite will abruptly increase the number of pores

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inside the diamond tools [7]. This will excessively weaken the performance of the matrix, and thereby greatly affect the service life of the diamond tools. Therefore, modification on the graphite surface was proposed. And the most common method is to plate a metal layer on the graphite surface [11,12]. It can make the surface have metallic properties, and remarkably improve the surface wettability of the graphite particles [13,14]. According to Ref. [10], a type of solid−solution interface bond will be formed at the interface between the graphite and the matrix materials by modifying the graphite surface. And it thereby significantly improves the interfacial bonding strength, and then the performance of the matrix can be enhanced. Among the various types of metal-coated graphite, nickel-plated graphite has been widely used due to its good comprehensive properties [15−17].

In previous work [7], nickel-plated graphite particles with different contents and unmodified graphite were added to Fe-based diamond saw blades. The results show that an appropriate amount of nickel-plated graphite particles can effectively increase the cutting efficiency of Fe-based diamond saw blades. Meanwhile, nickel plating can reduce the service life loss of Fe-based diamond saw blades caused by the addition of graphite particles. The study reveals that nickel-plated graphite can effectively adjust the working performance of diamond tools, further indicating that nickel-plated graphite has broad application prospects in diamond tools. However, the conclusions of Ref. [7] are only applicable to diamond saw blades and do not have wider applicability. The specific effect of nickel-plated graphite on the basic properties of the diamond tool matrix has less been clearly studied, which is related to the fundamental mechanism of nickel-plated graphite in diamond tools. At present, it is known that the addition of graphite particles will weaken the density, hardness, bending strength, wear resistance, and holding ability of diamond particles of the matrix. However, the specific weakening degree and weakening mechanism of those basic properties are still unclear. On the other hand, different diamond tools have different requirements for the basic properties of the matrix. For example, the matrix of diamond saw blades is required to have a good bending strength, while the matrix of diamond grinding wheels is required to have sufficient wear resistance [1]. Therefore, it is meaningful to fully explore the influence of nickel-plated graphite on the basic properties of the diamond tool matrix. Then, the application experience of nickel-plated graphite in more types of high-performance diamond products can be obtained.

In this work, Fe-based diamond composite samples with different contents of unmodified graphite particles and nickel-plated graphite particles were manufactured. Then, combined with the micromorphology characteristics and performance test data of the samples, the effect of nickel-plated graphite particles on the structure and properties of the sample is comprehensively studied. The results can provide experimental data support and theoretical guidance for the application of nickel-plated graphite in various high-performance diamond products.

2 Experimental

2.1 Preparation of Fe-based diamond composites

The matrix materials were selected according to the previous work [7] to obtain meaningful research results. Similarly, the particle size of Fe powder is 18 μm, and the particle size of Cu−Sn15, WC powder (Metallurgy and Materials Research Institute of Hunan Province, China) is 31−48 μm. The purity of all powders is above 99%. High-quality diamond particles (Henan Yellow River Cyclone Co., Ltd., China) with a volume fraction of 8.5% and a particle size of 325−380 μm were also selected based on previous application experience and research. According to the study on graphite particle size in Ref. [10], graphite particles with small sizes are helpful to the formation of graphite lubricating films. Therefore, unmodified graphite and nickel-plated graphite particles with a particle size of 20 μm were selected in this study, and their specifications are listed in Table 1. Also, according to Ref. [7], the mass fractions of them were set to be 0, 1%, 2%, 3%, and 4%, respectively. The proportions of all matrix components are listed in Table 2. The sintering temperature was set to be 860 °C, the holding time was 3 min, the vacuum degree was 0.1 Pa, and the sintering pressure was 65 MPa. Finally, samples with a size of 30 mm × 12 mm × 3 mm were prepared according to the ratios of components in Table 2. Diamond-containing samples and diamond-free samples

Table 1 Specifications of additives

Material	Size/μm	Theoretical density/(g·cm^{-3})	Mass fraction of Ni/%	Mass fraction of C/%	Purity/%
Graphite	20	2.15	0	100	>99
Nickel-plated graphite	20	7.25	75	25	>99

Table 2 Chemical compositions of matrix powder materials (wt.%)

Sample No.	Fe	Cu−Sn15	WC	Nickel-plated graphite	Graphite
1	70.00	15.00	15.00	−	−
2	69.30	14.85	14.85	1	−
3	68.60	14.70	14.70	2	−
4	67.90	14.55	14.55	3	−
5	67.20	14.40	14.40	4	−
6	69.30	14.85	14.85	−	1
7	68.60	14.70	14.70	−	2
8	67.90	14.55	14.55	−	3
9	67.20	14.40	14.40	−	4

were both prepared. In addition, a set of diamond composite samples containing nickel-plated graphite with different contents were prepared at a sintering temperature of 960 °C. They were used to study the influence of nickel-plated graphite particles on the thermal corrosion of diamond particles inside the matrix.

2.2 Characterization

The diamond-containing sample was used to determine relative density and bending strength, and the diamond-free sample was used to determine hardness and wear resistance. After sintering, the relative density of samples was determined according to the Archimedes law. And the hardness of the samples was determined in a TH300 Rockwell hardness tester (Shanghai Shuangxu Instrument Technology Co., Ltd., China). The bending strength was measured by the three-point flexural test method in a CMT4304 universal material testing machine (Shenzhen Shijitianyuan Instrument Technology Co., Ltd., China). The holding force coefficient was calculated according to the bending strength of the diamond-free samples and the diamond-containing samples. And it was used to evaluate the holding ability of the matrix to diamond particles [18]. The DHM-1 grinding wheel tester was used to measure the abrasion ratio of the diamond-free samples to evaluate the wear resistance of the samples [19]. In the above tests, each result was the average value of five identical samples. After the bending test, the resulting fracture surfaces of the tested samples were analyzed by using SEM equipped with EDS (X-Max^{N}, England). And the X-ray phase analysis of the diamond-free samples matrix and nickel-plated graphite particles was carried out (Bruke-D8 Advance, German). In addition, the morphology observation and elemental analysis of the original nickel-plated graphite particles were also carried out (Zeiss-Sigma300, German).

3 Results and discussion

3.1 Nickel-plated graphite particle characterization

Unlike the previous study [7], the nickel-plated graphite particles used in this study have a smaller particle size, and their morphology and surface elemental characteristics are shown in Fig. 1. From Fig. 1, the particles on the surface are Ni, and they show a good bonding state and a relatively uniform size. These Ni particles were plated on the surface of graphite particles by electroless plating. The EDS

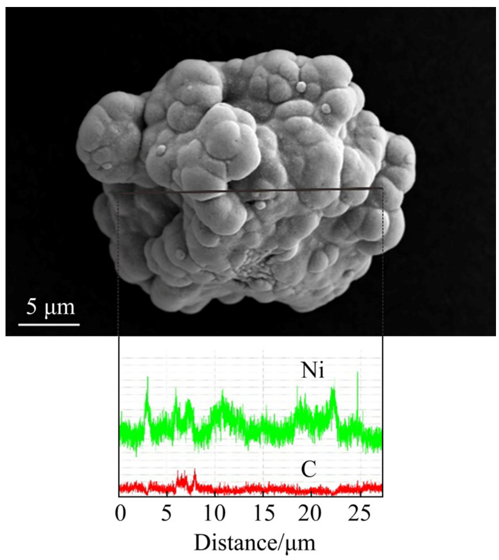

Fig. 1 Morphology and elemental analysis result of nickel-plated graphite particle

line-scanning result shows a remarkably low C element content on particle surface, demonstrating a good plating effect of Ni coatings. Figure 2(a) shows the phase analysis result of nickel-plated graphite particles. It can be seen that the diffraction peaks are clear, and there are no other components except the elementary phases of Ni and graphite. The characterization results show that the nickel-plated graphite particles used in the experiment are of good quality. Hence, the effect of nickel plating on the properties of Fe-based samples can be truly reflected in this study.

3.2 X-ray phase analysis of matrix materials

Figure 2(b) displays the phase analysis result of the matrix of diamond-free samples. It can be seen that it is mainly composed of the WC phase and (Fe,Ni) binder phase, as well as elementary phases of graphite and Ni. The absence of Cu and Sn components may be due to the extremely low content of liquid Cu−Sn15 in the matrix powder. According to the Fe−Ni phase diagram, there is a great solid solubility between Fe and Ni. Thus, a stable solid solution will be formed during the liquid sintering process and remain in the alloy structure. The diffraction peak intensity of the (Fe,Ni) binder phase in Fig. 2(b) is higher and the peak tip is narrow, indicating a good degree of crystallinity. It can be considered that the Fe in the matrix and the Ni on the surface of the graphite particles have reacted sufficiently. That is to say, a good metallurgical reaction has occurred between the nickel-plated graphite particles and the matrix materials.

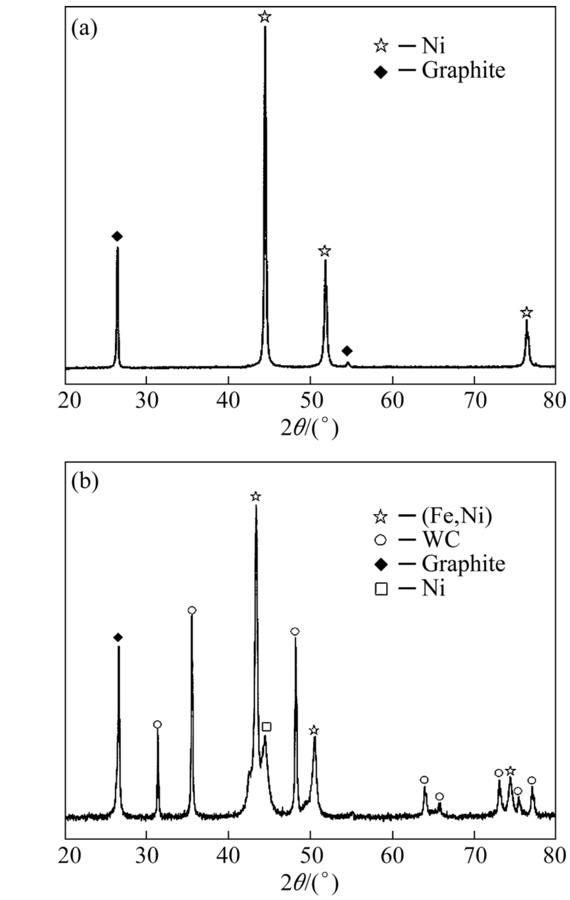

Fig. 2 XRD patterns of nickel-plated graphite (a) and diamond-free sample matrix (b)

3.3 Physical and mechanical properties

As shown in Fig. 3, the relative density, hardness and bending strength of the samples continue to decrease as the content of additives increases. And when the additive content is greater

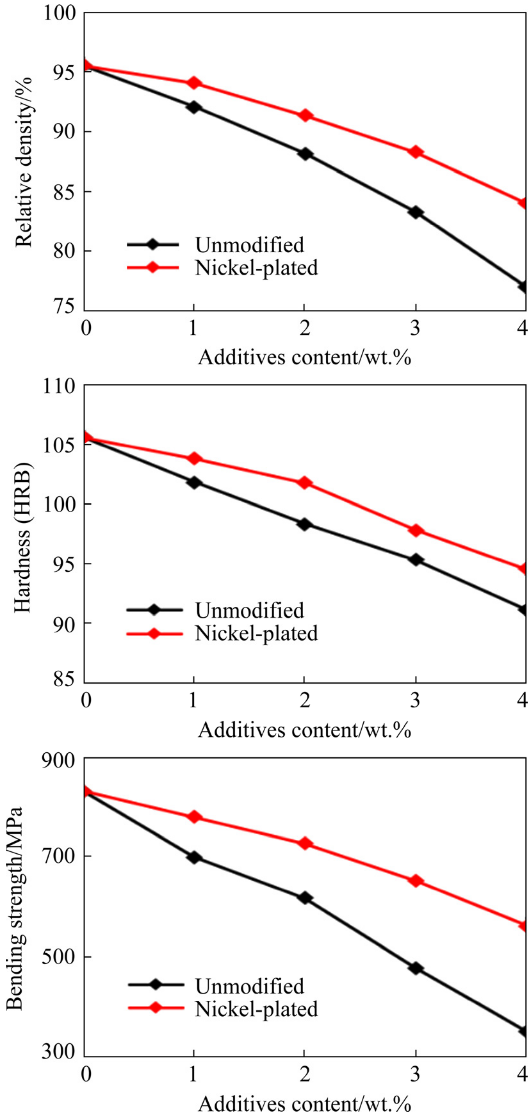

Fig. 3 Relationship of relative density (a), hardness (b), and bending strength (c) of samples and content of additives

than 2%, the properties of the samples show a greater range of change. This indicates an increasingly negative effect of adding graphite particles on the sample as the additives content increases. When the samples contain 4% unmodified graphite particles, their relative density, hardness and bending strength are decreased by 19.39%, 13.63% and 57.85%, respectively, compared with the sample without additives. And when the samples contain 4% nickel-plated graphite particles, their relative density, hardness and bending strength are decreased by 12.06%, 10.41% and 32.57%, respectively. This shows that nickel plating reduces the loss of relative density, hardness, and bending strength for the sample by 37.79%, 30.94% and 43.69% in this case. But according to the calculation result, when the samples contain 2% additives, the properties are reduced by 43.42%, 47.16% and 51.17%, respectively. To sum up, nickel plating can effectively alleviate the loss of physical and mechanical properties of the samples caused by the addition of graphite particles. But the effect brought by nickel plating is weakened with increasing the graphite content. On the other hand, it can be known that the bending strength of the sample has obtained the greatest extent of improvement. But the bending strength of the 4% nickel-plated graphite sample still dropped by 32.57%. Thus, diamond tools with higher requirements for bending strength should strictly control the nickel-plated graphite content.

According to Ref. [9], there is only the mechanical bond between the unmodified graphite particles and the matrix materials. Thus, the addition of unmodified graphite particles will generate a large number of pores and cracks inside the matrix. This causes a decrease in the density of the sample, which further affects the hardness and bending strength of the sample. In addition, graphite particles belong to the soft phase in the matrix material. That is to say, as the graphite content increases, the content of the soft phase in the matrix increases. And at the same time, the pores and cracks inside the matrix also increase. So, the ability to resist local plastic deformation of the matrix is greatly weakened, showing a great decline of the hardness. On the other hand, graphite particle has low surface energy, so the interfacial bonding strength between the graphite particles and the metal-bond materials is less than the cohesive strength between the metal-bond materials. Therefore, microcracks are prone to occur and continue to expand under the action of external forces, which finally causes a significant decline in the strength of the sample matrix.

Figure 4 shows the fracture morphology of the samples containing unmodified graphite particles. It helps to explain why the higher the content of additives is, the more severe the performance loss of the sample is. From Figs. 4(a, b), it can be seen that as the content increases from 2% to 4%, the distribution density of unmodified graphite inside the matrix increases. In this case, the probability of graphite particle clustering increases as well. Under the superposition effect, the pores and cracks around the agglomerated graphite particles will be connected, resulting in increased numbers and size of pores and cracks, as shown in Fig. 4(c). There are obvious gaps between the clustered unmodified graphite particles. This will cause a greater loss in the densification and strength of the sample. Also, the ability to resist local plastic deformation of the matrix will be further weakened so that the hardness will decrease further. It can be considered

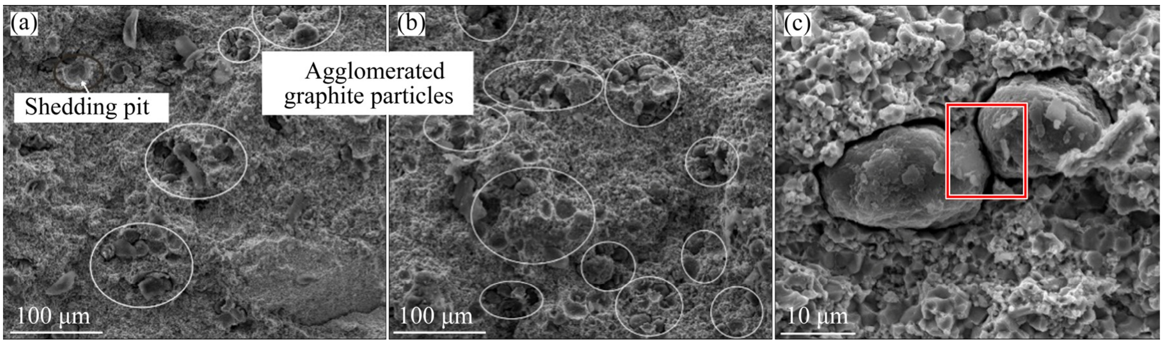

Fig. 4 Fracture morphologies of samples with different contents of unmodified graphite particles: (a) 2%; (b) 4%; (c) Agglomerated unmodified graphite particles

that the interfacial bonding strength between the graphite particles and the matrix material can be effectively improved after nickel plating. And this can help to reduce the generation of pores and cracks inside the matrix and thereby increase the density of the sample matrix.

Nickel plating also increases the plasticity of the sample matrix. It can be seen from Fig. 5 that the different additives cause the difference in fracture characteristics of the samples. The fracture morphology of the unmodified graphite sample (Fig. 5(a)) is mainly characterized by a mixture of intergranular fracture and transgranular fracture, accompanied by a small amount of dimple fracture. Due to the addition of graphite particles, there are many microcavities inside the sample (marked by the red arrow). Those microcavities are easy to expand along the grain boundary into brittle fracture along the grain, causing a decrease in the density and strength of the sample. Figure 5(b) displays the fracture morphology of the nickel-plated graphite sample. The mixed characteristics of intergranular fracture and transgranular fracture of the sample can be seen. But the proportion of transgranular fracture increases and more dimples appear. Meanwhile, as the bonding state of the nickel-plated graphite particles is improved, the number of microcavities is significantly reduced. Hence, it can be concluded that nickel plating increases the strength and plasticity of the samples, which is consistent with the mechanical property data in Fig. 3. In the actual work process, diamond tools need to possess certain physical and mechanical properties, which play an essential role in guaranteeing the working efficiency and service life of the tools.

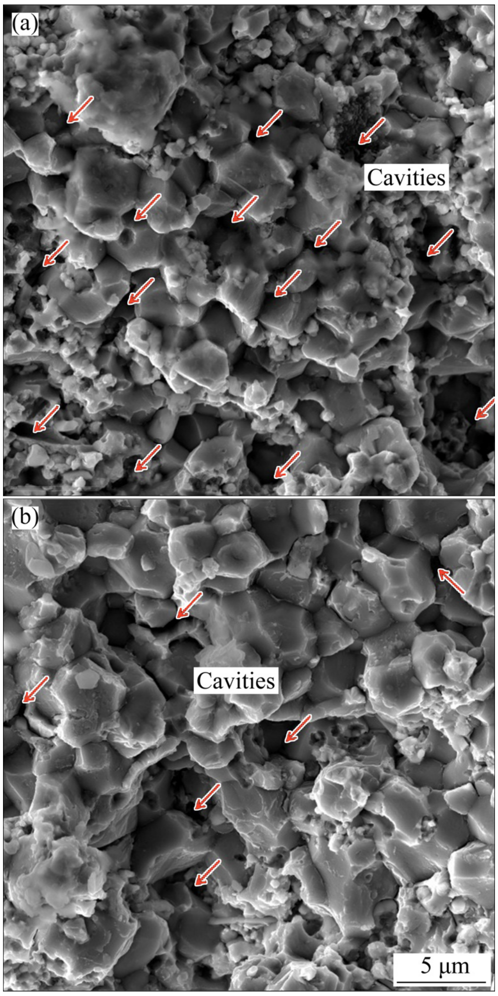

Fig. 5 Fracture morphologies of 2% unmodified graphite sample (a) and 2% nickel-plated graphite sample (b)

3.4 Wear resistance and holding ability

According to the matrix weakening theory of the diamond tools [7], reasonably reducing the wear resistance of the tool matrix can effectively improve its working efficiency. However, the wear resistance weakening of the tool matrix is usually accompanied by a reduction in its service life. On the other hand, to a certain extent, the holding ability represents the actual utilization of diamond particles during the working process of the tool. Therefore, the higher the holding coefficient is, the better the service life of the tool can be guaranteed [7]. As shown in Fig. 6, the wear resistance and holding ability to diamonds of the sample gradually decrease with the increase of additive content. And similarly, when the additive content is greater than 2%, performance parameters show a greater range of changes. When the sample contains 4% unmodified graphite particles, its wear resistance and holding ability to diamonds are decreased by 50.38% and 60.43%, respectively, compared with the sample without additives. This reflects the great impact of adding graphite on the working performance and service life of the diamond tool matrix. And also, the calculation results show that nickel plating reduces the loss of wear resistance and holding ability by 57.44% and 32.39%, respectively, demonstrating the significant role of nickel plating. But when the content of additives in the matrix is only 2%, nickel plating can reduce the loss of the wear resistance and the holding ability of the sample by 65.13% and 41.72%, respectively. Hence, similar conclusions

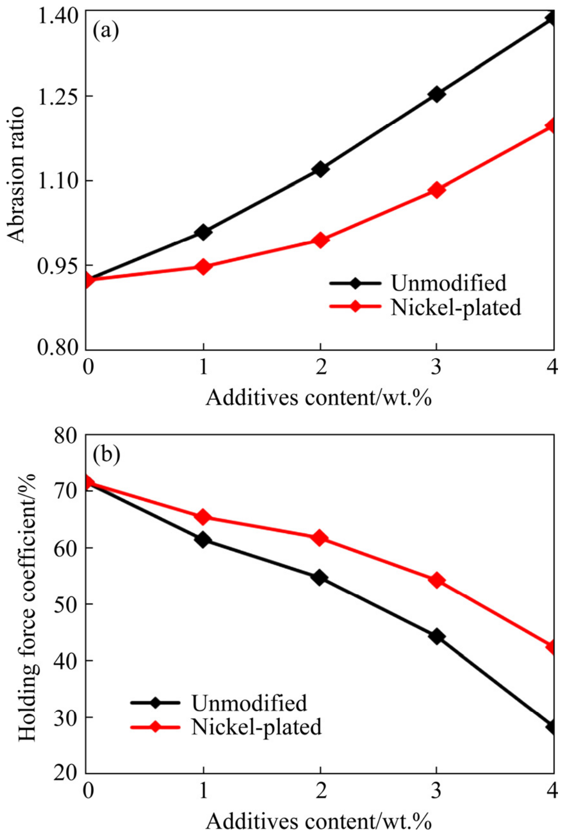

Fig. 6 Relationship between abrasion ratio (a) and holding force coefficient (b) of samples and additives content

can be drawn that the effect brought by nickel plating is weakened as the graphite content increases.

3.4.1 Influence of nickel plating on wear resistance

Figure 7 shows the morphologies of grinding surfaces of three representative samples. It can be seen that after grinding, graphite lubricating blocks are precipitated on the grinding surfaces of the two types of samples with 2% additives. And further observation shows that there is little difference in their quantity and distribution. Flake films cannot be formed. However, the wear condition of the matrix structure of each sample is different. As displayed in Fig. 7(a), the grinding surface of the sample without additives is distributed with grinding grooves with a certain uniformity in width and depth. This indicates that the indentation ability of wear-resistant particles in each area of the grinding surface is almost the same, so the wear condition is almost identical. On the other hand, it can be found that the grinding grooves in Figs. 7(b, c) are significantly affected by the distribution of graphite particles. That is to say, due

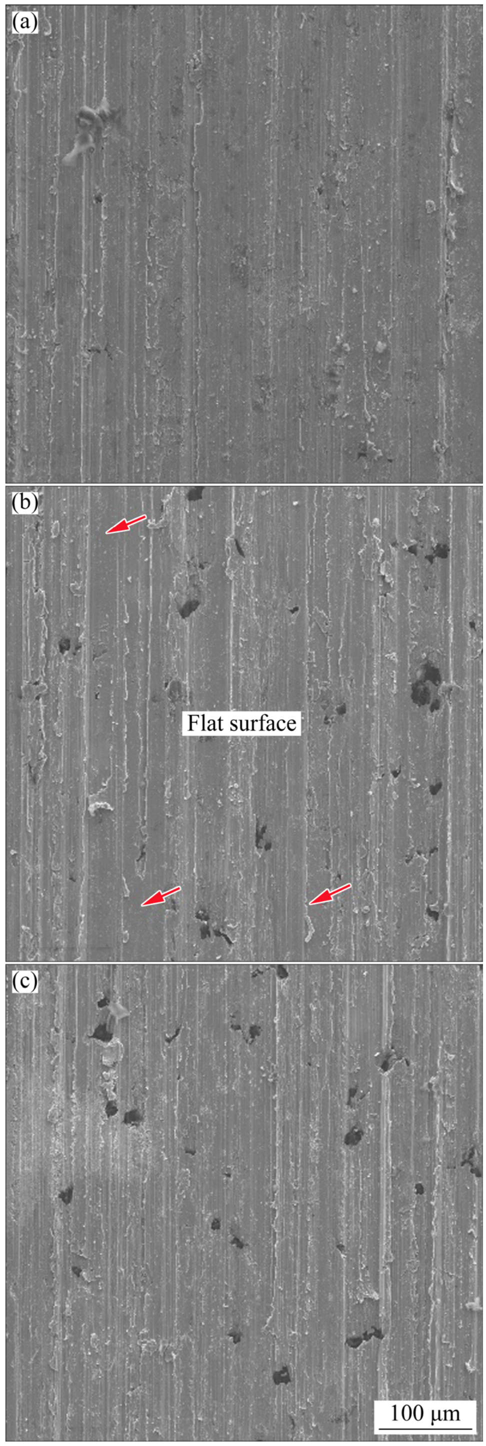

Fig. 7 Morphologies of grinding surfaces of different samples after grinding test: (a) Without additives; (b) 2% unmodified graphite sample; (c) 2% nickel-plated graphite sample

to the presence of soft graphite particles in some areas, the penetration depth of the graphite is greater. It can be seen that the grinding grooves are deep and wide, and the grinding surface shows severe wear as well. Further observation finds that the wear of the samples is also different due to various additives. By comparison, wider and deeper grinding grooves can be found on the grinding surface of the unmodified graphite sample, (marked by red arrows). It can be learned from Refs. [18] and [19] that these wider grinding grooves represent a lower wear resistance and hardness of the sample matrix. Thus, the observation results of the grinding surface are consistent with the data in Fig. 6(a). That is to say, the addition of unmodified graphite particles will weaken the ability of the matrix to resist the intrusion of standard grinding wheel abrasive particles, thereby showing a low wear resistance. But the wear resistance can be effectively improved when the graphite particles are plated with nickel. Besides, it is reasonable to speculate that when the diamond tool matrix contains graphite particles, the area where the graphite particles gather will wear first [20]. Therefore, the content of the nickel-plated graphite particles in diamond tools should be reasonably determined. Also, the appropriate dispersibility of graphite particles should be kept. These are of great significance to the improvement of tool performance.

3.4.2 Influence of nickel plating on holding ability

When graphite particles are contained in the diamond tool matrix, the research object of the matrix holding ability should include both the diamond particles and graphite particles. Figure 8 shows the effect of graphite particles inside the matrix on diamond particles. It can be seen from Fig. 8(a) that when there are no additive particles in the matrix, the diamond particle is in close contact with matrix materials. And there are almost no gaps in the transition interface, indicating effective retention of the matrix to the diamond particle. After adding graphite particles into the matrix, a large number of pores and cracks are generated. In this case, the pores and cracks generated around the graphite particles closer to the diamond particles interact with the peripheral gaps of the diamond particles (Fig. 8(c)). Eventually, the gaps around the diamond particles increase (Fig. 8(b)), which greatly affects the retention state of the diamond particles inside the matrix. Therefore, if the interface bonding state between the graphite particles and the matrix materials can be effectively improved, the holding state of the diamond particles will also be improved. In addition, the interface bonding state between graphite particles and matrix material before and after nickel plating is further studied.

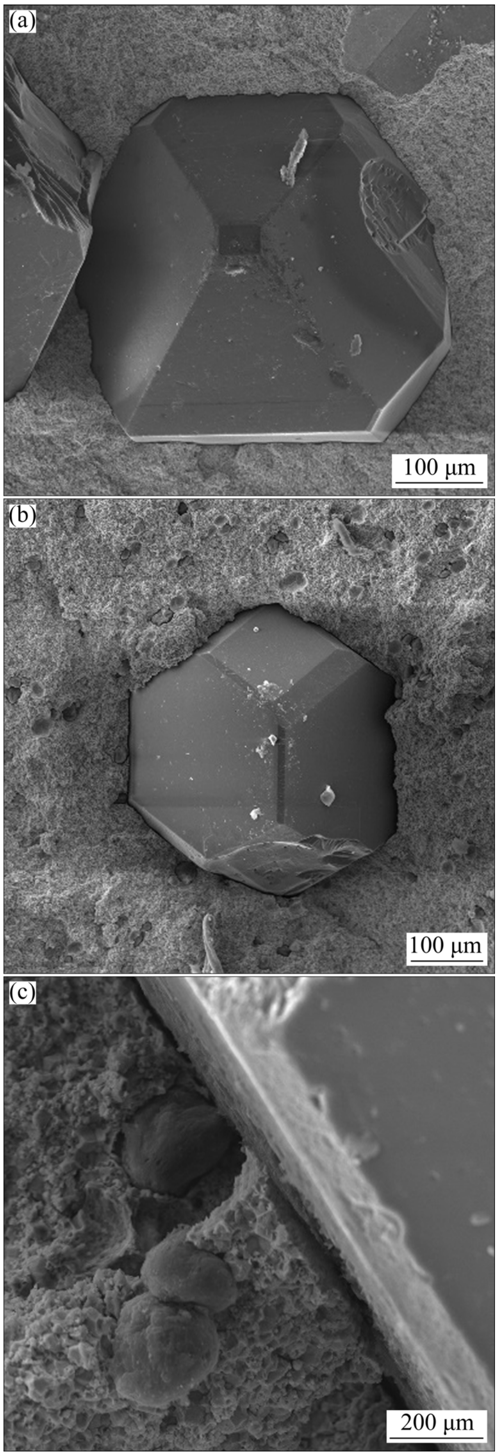

Fig. 8 Morphologies of diamond particles inside sample without additives (a) and with unmodified graphite particles (b), and boundary superimposition effect of two types of particles (c)

Figure 9(a) shows the result of elemental analysis on the surface of unmodified graphite particles. It can be seen that there is almost the C element only. Moreover, the graphite particle has obvious edge seams. In this case, it can be considered that there is only the mechanical bond between this graphite particle and the matrix materials. On the other hand, as shown in Fig. 9(b), elemental analysis of the shedding pit of the nickel-plated graphite shows that a large amount of C and Ni elements are detected in the bottom of the shedding pit of nickel-plated graphite particles. This demonstrates that a good metallurgical reaction occurs between the nickel-plated graphite particle and the matrix material. And then, further morphological observation and elemental analysis of the nickel-plated graphite particle (Fig. 10) show that there is a complete transition interface between the nickel-plated graphite particle and the matrix materials, which has obvious metallurgical bonding characteristics. Also, abundant Fe, Ni, and C elements are detected on the transition interface, indicating that an effective element diffusion zone is formed. WANG et al [21] pointed out that the

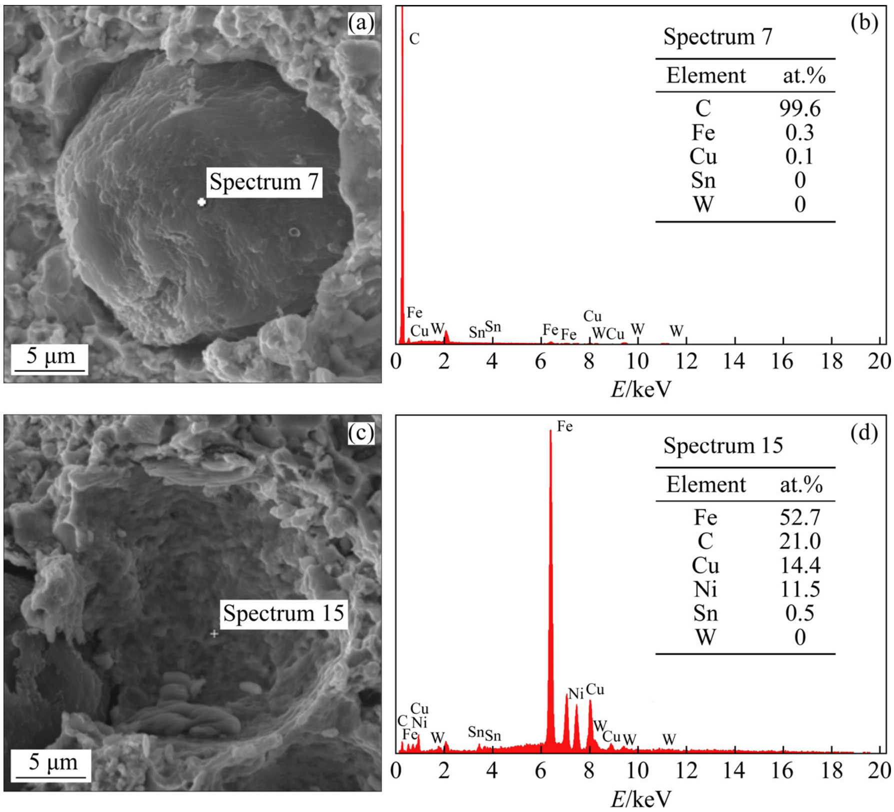

Fig. 9 Morphologies and elemental analysis results of unmodified graphite particles (a, b) and shedding pit of nickel-plated graphite particle (c, d)

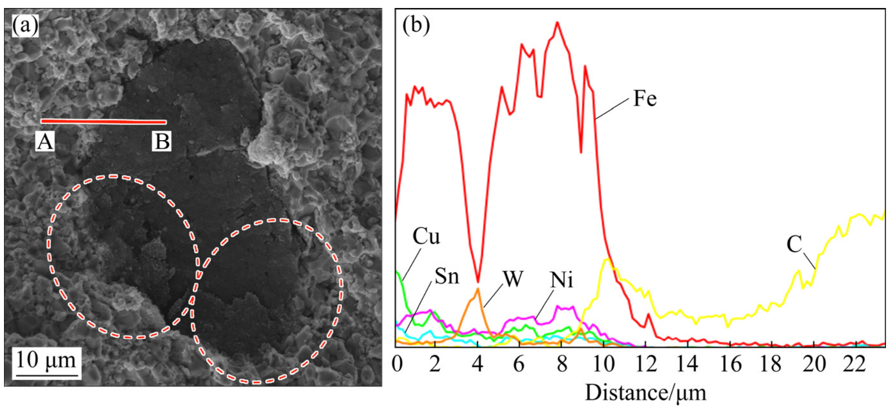

Fig. 10 Morphology of individual nickel-plated graphite particles inside sintered sample matrix (a) and elemental line-scanning results (b)

nickel-plating layer can generate an element diffusion zone in the transition interface, reducing the activation energy of diffusion and increasing the driving force of diffusion. In this study, due to the excellent solid solubility between Fe and Ni, nickel plating makes the transition interface have higher diffusion strength. As a result, the diffusivity of substances at the interface is effectively enhanced, increasing the bonding strength of the interface. Based on the above, it can be concluded that the matrix can effectively retain nickel-plated graphite particles.

Nickel plating can not only improve the interface bonding state between the nickel-plated graphite particle and the matrix materials, but also effectively improve the boundary of agglomerated graphite particles, as shown in Fig. 11. It can be seen that the two sides of the junction of the two nickel-plated graphite particles are filled with matrix materials (marked by red arrows) and almost leave no gaps. This is in sharp contrast with Fig. 4(c). And the EDS line-scanning result proves that the Fe element reaches a peak at the junction of the two nickel-plated graphite particles. It can be considered that there is still a good metallurgical bond there. Hence, nickel plating for graphite particles can undoubtedly effectively reduce the generation of various pores and cracks inside the matrix due to the addition of graphite particles. In addition, it is known that those graphite particles and diamond particles in the poor bond will fall off and fail in advance during the working process, affecting the working efficiency and service life of the tool. Therefore, it can also be concluded that nickel plating can improve the work efficiency and service life of diamond tools by enhancing the ability of the matrix to hold both graphite particles and diamond particles.

In summary, by changing the content of nickel-plated graphite particles, it is possible to adjust the wear resistance and holding ability of the diamond tool matrix. Combined with the discussion in the previous studies on nickel-plated graphite diamond saw blades [7], the wear resistance and holding ability are eventually reflected in the working efficiency and service life of the tool. Hence, when different diamond tools have different requirements for work efficiency and service life, flexible adjustment of the nickel-plated graphite content can maximize the function of the tool. For example, in the emergency rescue process of geological disasters, drilling tools must provide a high drilling efficiency. In this case, an impregnated diamond drill bit containing an appropriate amount of nickel-plated graphite particles can help achieve the goal quickly.

3.5 Lubrication and heat conduction of nickel-plated graphite

3.5.1 Formation law of graphite lubricating film

To explore the formation law of graphite lubricating film, the microscopic morphology of the grinding surfaces of the samples with different nickel-plated graphite contents was observed. The results show that only graphite lubricating blocks are distributed on the sample with 2% nickel-plated graphite (Fig. 7). When the nickel-plated graphite content is increased to 3%, some small-area flake films appear on the grinding surface (Fig. 12(a)). Until the nickel-plated graphite content is increased to 4%, as shown in Fig. 12(b), ideal flake graphite lubricating films are formed on the grinding surface of the sample, with a larger area and a denser distribution. This may be because the nickel-plated

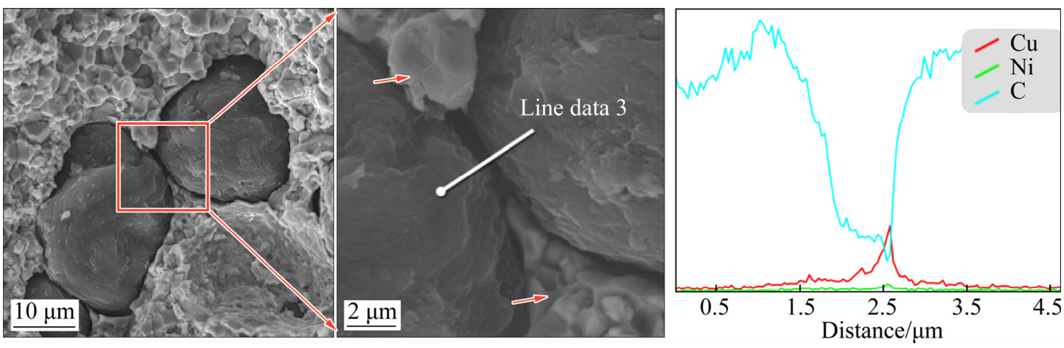

Fig. 11 Morphologies of agglomerated nickel-plated graphite particles inside sample matrix and elemental line-scanning results

graphite particles used in this study have a small particle size and strong dispersibility. When the graphite component precipitating in a certain area on the working surface is too low, it will not converge into a graphite lubricating film before the lubricants are completely consumed. Therefore, it can be reasonably inferred that within a certain range, the content of nickel-plated graphite is positively correlated with the quality of the graphite lubricating films formed on the working surface. In addition, elemental determination of the lubricating film shows that it mainly contains Cu and Sn elements in addition to C and Ni. That is to say, the Cu−Sn15 also participates in the precipitation of graphite lubricating films after being completely transformed into the liquid phase. It can be inferred that adding some specific components to the matrix can cause the formation of graphite lubricating film.

On the other hand, it is found that there are almost no graphite particles on the grinding surface when the graphite lubricating blocks and graphite lubricating films exist on the grinding surface. This indicates that the nickel-plated graphite particles have been completely converted into lubricants before they are exposed. On this basis, the graphite lubricating films at various precipitation stages were further studied, as shown in Fig. 13. It can be

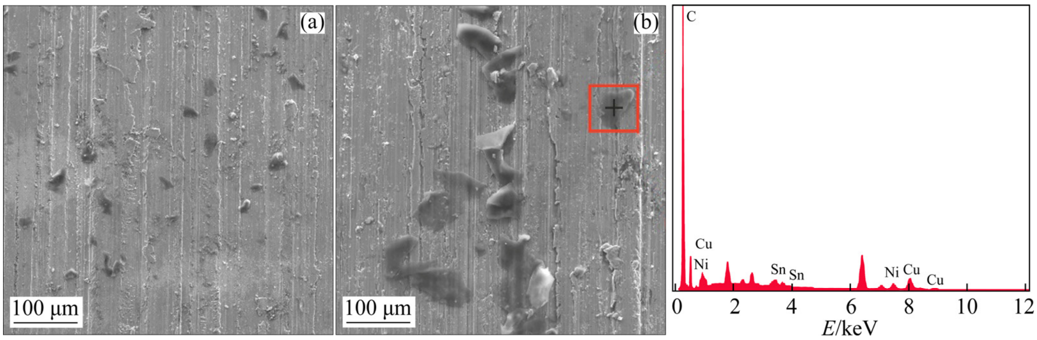

Fig. 12 Grinding surface morphologies of samples with different nickel-plated graphite contents and corresponding EDS results: (a) 3%; (b) 4%

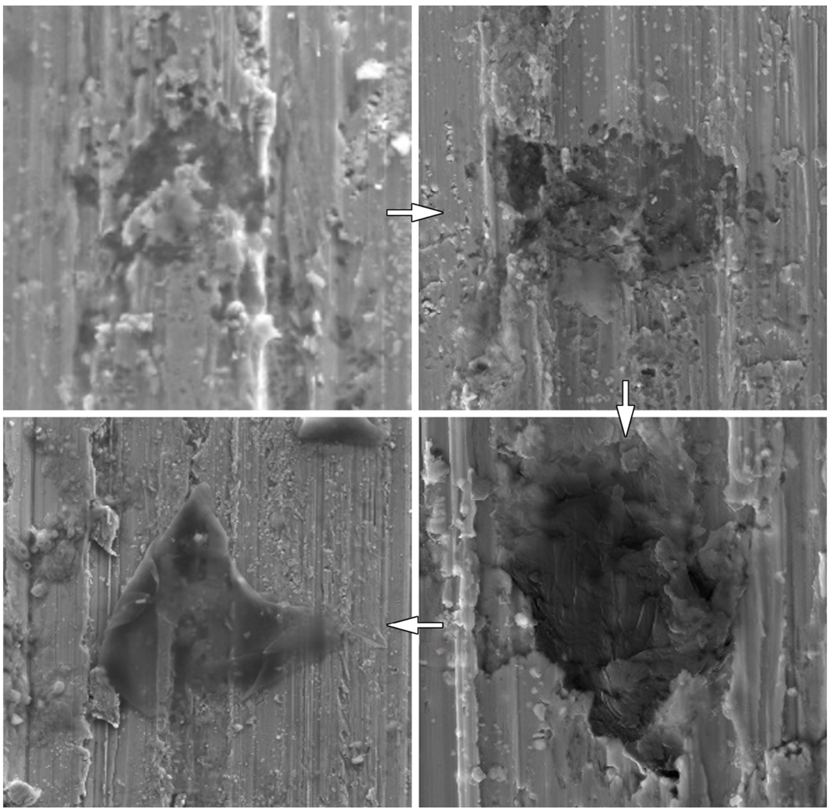

Fig. 13 Different formation stages of graphite lubrication film

concluded that the graphite particles on the outer edge of the matrix have gradually transformed into lubricants under the action of high-temperature extrusion before they are exposed to the working surface. These lubricants first accumulate inside the matrix, and only a small part precipitates on the grinding surface. Then, as the matrix is gradually ground, the graphite lubricants are gradually exposed. It should be noted that the graphite particles are not transformed into lubricants after falling out of the matrix. Therefore, the effective retention of graphite particles inside the matrix can help to form graphite lubricants. That is to say, nickel plating plays a significant role in forming the lubricants on the working surface. However, according to the previous application research of nickel-plated graphite in diamond saw blades, too many graphite lubricating films will cause a decrease in the cutting efficiency [7]. In that case, the rock cutting action of diamond particles is transformed into an elastic deformation due to the thick lubricating film. Hence, it is crucial to control the content of nickel-plated graphite inside the diamond tool matrix. A suitable amount of graphite lubricating film can effectively guarantee the utilization rate of diamond particles, thereby increasing the working efficiency and service life of the diamond tool.

3.5.2 Thermal corrosion of diamond

The micromorphology of diamond particles inside the nickel-plated graphite sample sintered at 960 °C was observed, as shown in Fig. 14. It can be seen that the metal thermal corrosion occurs on the surface of different diamond particles, which is consistent with the previous study [7]. At a sintering temperature of 960 °C, the α-Fe in the matrix transforms into γ-Fe and then etches diamond [22]. However, it can be found that different diamond particles suffer various degrees of thermal corrosion. It is known that heat plays a significant role in the degree of thermal corrosion [23]. When the content of nickel-plated graphite particles in the matrix is higher, the graphite particles around the diamond particles that can perform reliable heat conduction increase, so the degree of thermal corrosion is relatively lighter. In comparison, the thermal corrosion area on the surface of the diamond particles inside the 4% nickel-plated graphite sample is smaller, and the localized corrosion shrinks into pitting corrosion. Also, the corrosion depth is reduced, and the edge corrosion of diamond particles is also improved. This improvement in thermal corrosion generally indicates that the matrix has an improved ability to hold diamond particles. Therefore, the results indicate that nickel plating is conducive to the retention state of the diamond particles. On the other hand, it can be concluded that if an appropriate amount of nickel-plated graphite particles are added into the metal-bond diamond tool matrix, the upper limit of the sintering temperature can be broadened. In this way, the selection range of diamond tool matrix materials can also be broadened because many materials that require higher sintering temperatures can be used.

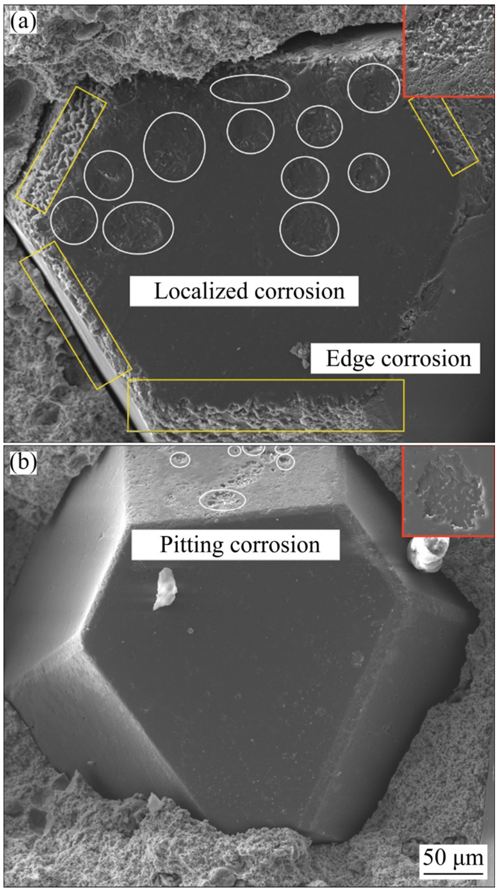

Fig. 14 Surface morphologies of diamond particles of different samples: (a) 1% nickel-plated graphite sample; (b) 4% nickel-plated graphite sample sintered at 960 °C

4 Conclusions

(1) Adding unmodified graphite particles generates a large number of pores and cracks inside the matrix, which significantly affects the basic

properties of the diamond tools. And the higher the unmodified graphite content is, the greater the impact is.

(2) Nickel plating can remarkably enhance the surface wettability of graphite particles. By nickel plating, an effective element diffusion zone is formed on the transition interface between graphite particles and matrix materials, thereby enhancing the interfacial bonding strength. This effectively reduces the pores and cracks generated inside the matrix, thereby enhancing the basic properties of the matrix containing graphite particles. Besides, nickel plating can simultaneously improve the utilization of graphite particles and diamond particles inside the diamond tool matrix.

(3) The forming quality of graphite lubricating films is positively related to the content of nickel-plated graphite. In addition, it is found that during the grinding process, the graphite lubricants are first formed inside the matrix and then gradually exposed. Therefore, nickel plating for graphite particles plays a significant role in forming graphite lubricating films.

(4) During the high-temperature sintering process, arranging nickel-plated graphite particles inside the matrix can reduce the thermal corrosion of diamond particles, which helps improve the utilization of diamond particles.

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镀镍石墨对铁基金刚石工具胎体微观结构和性能的影响

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摘　要：将不同含量的镀镍石墨颗粒和未经处理的石墨颗粒添加到铁基金刚石复合材料试样中，采用 SEM、XRD 和 EDS 对试样进行微观结构表征、物相分析和元素分布测试，并测定试样的相对密度、硬度、弯曲强度、磨损量及其胎体对金刚石的包镶能力。结果表明，镀镍能有效改善石墨颗粒的表面润湿性，并在镀镍石墨和胎体组织间的过渡界面上形成元素充分扩散的区域，这有效增强石墨颗粒与胎体组织间的界面结合强度。镀镍后石墨颗粒在胎体组织内部形成的孔隙和裂纹减少，因此，镀镍能抑制由于添加石墨颗粒给试样造成的基础性能损失，但添加物含量越高，镀镍的抑制效果越差。此外，镀镍能够有效保障工作面上石墨润滑物的形成，且高温烧结下镀镍石墨有助于减轻试样内部金刚石颗粒的热腐蚀。

关键词：金刚石复合材料；镀镍石墨；微观结构；力学性能；润滑机理

(Edited by Bing YANG)