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Application of pre-alloyed powders for diamond tools by ultrahigh pressure water atomization

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Abstract: Copper, iron and cobalt based pre-alloyed powders for diamond tools were prepared by ultrahigh pressure water atomization (UPWA) process. Pre-alloyed powders prepared by different processes including UPWA, conventional water atomization (CWA) and elemental metal mechanical mixing (EMMM) were sintered to segments and then compared in mechanical properties, holding force between matrix and diamond, fracture morphology of blank and sintering diamond section containing matrix. The results showed that the pre-alloyed powder prepared by UPWA exhibits the best mechanical properties including the relative density, the hardness and the bending strength of matrix sintered segment. Sintered segments fractography of UPWA pre-alloyed powder indicates mechanical mosaic strength and chemical bonding force between the pre-alloyed powder and the diamond, leading to the great increase in the holding force between matrix and diamond. The mechanical performance and the service life of diamond tools were greatly improved by UPWA pre-alloyed powders.

Key words: ultrahigh pressure water atomization; pre-alloyed powders; diamond tools; sintered segments

1 Introduction

In diamond tools industry, the traditional way to prepare metal matrix powder is EMMM method, which is difficult to achieve the pre-alloyed powder matrix and easily leads to powder oxidation, inhomogeneous matrix composition and solute segregation [1−3]. The control force between matrix material and diamond is poor, which results in poor mechanical properties of diamond tools, and short service life [4−6].

The elements can form intermetallic compounds and achieve partial or complete mutual dissolution during the preparation of pre-alloyed powder. Components segregation of matrix powder can be avoided, especially when all pre-alloyed powders are consistent with the nominal element composition [7]. By using the matrix pre-alloyed powder, activation energy can be greatly reduced, and thus reducing the sintering temperature and avoid the strength loss [8]. On the other hand, the microstructure of matrix is more uniform, and the density, the hardness and the bending strength of matrix are improved significantly, leading to the improvements in control force mechanical properties and service life of the diamond tools [9,10]. The process using pre-alloyed powder can be able to solve the uniform mixing problem of matrix powder, and enhance elements of matrix material which realize a fully coverage and contact between diamond.

The concept of using pre-alloyed powder in diamond tools was proposed by Umicore Corporation in Belgium since 1990s [11]. Researchers all over the world made a lot of efforts to the application of pre-alloyed powder in diamond tools [12−14]. At present, the main preparation method of the pre-alloyed powder for diamond tools is water atomization method and hydrometallurgical co-precipitation method [15−18]. Conventional water atomization method shows disadvantages of coarse particle size and high oxygen content in products, which limited its application [19,20]. UPWA technology, considered as the most effective way to improve the diamond tools performance, is based on conventional atomization technology and developed by spray nozzle optimization, atomization device design and rapid solidification technology. The pre-alloyed powder prepared by this method shows fine particle size, uniform

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composition segregation, low oxygen content, controllable particle morphology and low production cost [21,22]. In the present work, to explore the advantages of UPWA, three kinds of pre-alloyed powders were prepared by UPWA, CWA and EMMM separately. The powders were sintered to segments and compared in properties. Moreover, the fracture morphologies of sintered segments were characterized to explain their property differences.

2 Experimental

2.1 Materials and equipment

The experimental powders of copper, iron and cobalt based alloy were prepared by UPWA and CWA, and the powder produced by EMMM method was purchased. Technical performance of UPWA powder, water atomization powder and mechanical mixing metal matrix powder used in the experiment is listed in Table 1. The chemical composition of matrix powder material is listed in Table 2. Figure 1 exhibits the particle morphologies of UPWA pre-alloyed powders. Tables 1 and 2 show that the average particle size and the oxygen content of UPWA pre-alloyed powder are far lower than those of the EMMM matrix powder, and also show a certain decrease compared with CWA pre-alloyed powder.

Both the blank and the diamond added matrix materials with a size of 40 mm × 8 mm × 32 mm were prepared by SMVB60 vacuum sintering machine.

2.2 Sintered segment preparation

Matrix powder and diamond were uniformly mixed and then enclosed into graphite mold. Graphite mold was placed into an electrode pressure head. At 800−1000 °C, the metal matrix material was melted and combined with diamond. The sintered segment of diamond tool was prepared by a following cooling, mould unloading and polished smooth.

The diamond tool sinter segment preparations with blank and with diamond were similar. Blank diamond tool sintered segment preparation includes the procedures as testing of raw materials, mold assembly, weighting, feeding, loaded indented, hot pressing, cooling, unloading mode, polishing smooth, measurements, weighing and performance testing. Diamond tool sintered segment preparation includes the procedures as testing of raw materials, burden, mixture, mold assembly, weighting, feeding, loaded indented, hot pressing, cooling, unloading mode, polishing smooth,

Table 1 Technical performance of UPWA powder

Number	Average particle size/μm	Apparent density/(g·cm^{-3})	Morphology	Matrix powder type
A1	16.98	3.1	Spherical	UPWA Cu-based pre-alloyed powder
B1	34.56	3.3	Spherical	CWA Cu-based pre-alloyed powder
C1	52.28	3.5	Near spherical, dendritic	EMMM method Cu-based pre-alloyed powder
A2	17.67	3.0	Spherical	UPWA Fe-based pre-alloyed powder
B2	35.72	3.3	Spherical	CWA Fe--based pre-alloyed powder
C2	53.45	3.5	Near spherical, dendritic	EMMM method Fe-based pre-alloyed powder
A3	14.66	3.2	Spherical	UPWA Co-based pre-alloyed powder
B3	35.05	3.4	Spherical	CWA Co-based pre-alloyed powder
C3	51.78	3.6	Near spherical, dendritic	EMMM method Co-based pre-alloyed powder

Table 2 Chemical composition of matrix powder material (mass fraction, %)

Number	Cu	Fe	Co	Sn	Zn	Ti	Cr	WC	Ce	O
A1	60.15	24.05	−	4.91	4.83	1.95	1.98	−	1.96	0.085
B1	60.08	24.04	−	4.92	4.81	1.96	1.97	−	1.95	0.128
C1	59.94	24.02	−	4.85	4.78	1.94	1.95	−	1.97	0.482
A2	30.18	55.14	−	5.82	5.78	−	−	−	2.93	0.092
B2	30.05	55.08	−	5.79	5.76	−	−	−	2.94	0.145
C2	29.93	54.92	−	5.78	5.74	−	−	−	2.96	0.492
A3	30.04	15.04	35.12	7.80	7.76	−	−	4.06	−	0.081
B3	30.02	14.98	35.05	7.83	7.74	−	−	4.05	−	0.136
C3	29.91	14.92	35.02	7.82	7.70	−	−	4.08	−	0.452

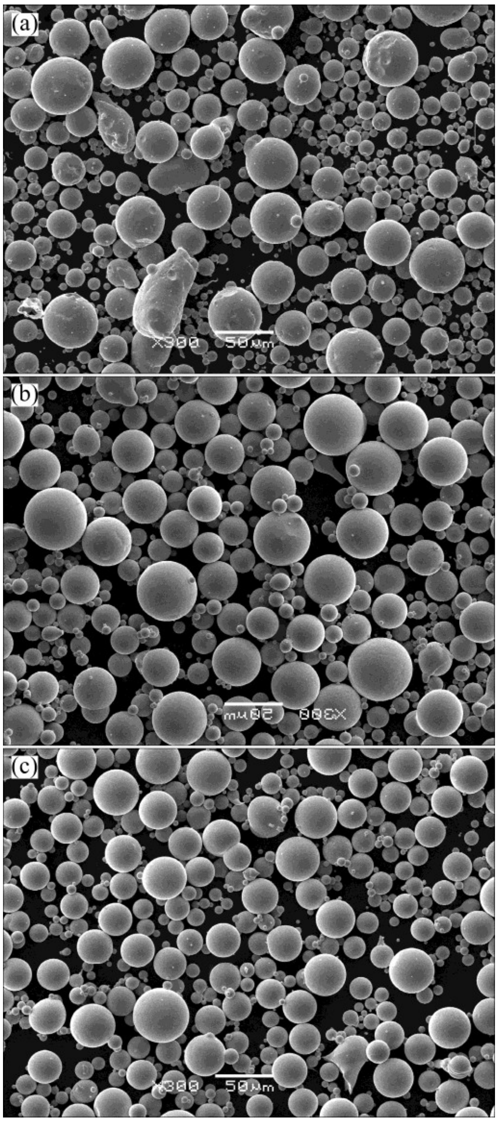

Fig. 1 Particle morphologies of UPWA powders: (a) Cu-based; (b) Fe-based; (c) Co-based

measurements, weighing and performance testing.

Liquid phase sintering process was used in all experiments. Parameters and operating procedures of the sintering process are listed in Table 3.

2.3 Performance characterization

The chemical composition of matrix powders was analyzed with a WFX−120 atomic absorption spectrometer and a TC−436 nitrogen-oxygen analyzer. Morphology of matrix powder particle was observed with a JSM−6360LV scanning electron microscopy. The average particle size of powder was measured by LS800 laser particle size analyzer.

The hardness of sintered segment was measured with an HR−150A Rockwell hardness. The bending strength of the sintered segment was tested by Nodal LD−508 type universal testing machine. The density of sintered segment was measured by drainage method. Fracture morphology of sintered segment was observed with a JSM−6360LV scanning electron microscope.

Table 3 Parameters and operating procedures of sintering process

Temperature range	Time/min	Heating rate/(°C·min^{-1})	Pressure/MPa
Room temperature to 600 °C	4	150	9
600 °C to sintered temperature	1.5	106	30
Sintered temperature	2	0	30
Cooling	0.5	0	30

3 Results and discussion

3.1 Mechanical properties of matrix diamond products

Table 4 lists the mechanical properties of sintered segments of Cu-based pre-alloyed powder prepared by UPWA, CWA and EMMM methods under the same composition recipe and sintering conditions.

It is found that the relative density, hardness and bending strength of sintered segments prepared by UPWA powders are higher than those prepared by EMMM. Diamond tool sintering is a process of powder curing to remove the holes. During the sintering, the pre-alloyed powder forms fine particle size and large surface area, which has a faster diffusion velocity to transform the hollow surface with high energy into solid crystals with low energy. The relative density, the hardness and the bending strength of diamond tools have been significantly improved. Therefore, the pre-alloyed powders have a higher bending strength than the powders prepared by EMMM method [23].

Table 4 also shows that compared with the CWA pre-alloyed powder, the UPWA pre-alloyed powder has the advantages of fine average particle size and low oxygen content, and the relative density, the hardness and the bending strength have also been improved.

3.2 Holding force calculation of matrix to diamond

Generally speaking, the interface between diamond and matrix is the source of fracture. So, the bending strength of sintered segments with diamond is lower than the ones with blank. The decreased value of bending strength can be used to measure the holding force of matrix to diamond [24]. The holding force coefficient (F) is calculated as follows:

$$Q=(\sigma_b-\sigma_d)/\sigma_b \quad (1)$$

$$F=100(1-Q) \quad (2)$$

where Q is the decreased bending strength value between diamond sintered segments and blank sintered segments; F is the holding force coefficient of matrix to diamond.

Under the same condition of ingredient formula and sintering process, the holding force coefficients of different matrix to diamond are listed in Table 5. The results show that the pre-alloyed powders, especially the UPWA powders, have a strong holding force to diamond. The oxygen content of UPWA pre-alloyed powder is reduced, leading to a higher holding force of matrix to diamond compared with the CWA pre-alloyed powder.

In diamond tools, diamond particles are generally distributed in the matrix. The cutting tools are abrased with matrix material during cutting stones. This makes the diamond particles abrased continuously [25,26]. So the losing degree of diamond during sawing process is an important indicator. Table 6 exhibits the calculation results of the losing degree of diamond during the sawing process under the same ingredient formula and sintering condition.

The losing degree of matrix segments prepared by the UPWA powders is lower than the ones prepared by EMMM powders. It is shown that the pre-alloyed powders prepared by UPWA have stronger holding force to diamond than CWA powders. This is consistent with the holding force coefficient results above.

3.3 Fracture analysis of blank matrix sintered segment

Figure 2 shows the fracture morphology of blank matrix sintered segment using Cu-based pre-alloyed powder prepared by UPWA, CWA and EMMM. It is found that the fracture morphology of the blank matrix sintered segment with pre-alloyed powder prepared by UPWA is dense and dimple, which is the typical characteristic of ductile material (Fig. 2(a)). As shown in Fig. 2(b), the fracture morphology of the blank matrix sintered segment with the CWA pre-alloyed powder is also dimple, but becomes larger compared with one in Fig. 2(a), which means a decrease in toughness of the matrix. In Fig. 2(c), the fracture morphology of the blank matrix sintered segment with the alloy powder prepared by EMMM shows smooth surface, which is the typical characteristic of brittle material. Accordingly, the fracture morphology of the blank matrix sintered segment using the pre-alloyed powder is ductile, while the one using EMMM powder is brittle. Conclusions can be obtained that the pre-alloyed powder has a significantly stronger holding performance to diamonds than the EMMM powder. The UPWA pre-alloyed

Table 4 Mechanical properties of sintered segments

Segment number	Powder number	Relative density/%	Hardness (HRB)	Bending strength		Matrix powder type
				σ_b/MPa	σ_d/MPa	
X1	A1	99.5	98.4	964	825	UPWA Cu-based pre-alloyed powder
Y1	B1	99.2	96.2	940	776	CWA Cu-based pre-alloyed powder
Z1	C1	97.3	88.5	876	654	EMMM Cu-based pre-alloyed powder
X2	A2	99.6	103.3	1075	904	UPWA Fe-based pre-alloyed powder
Y2	B2	99.2	101.2	1030	838	CWA Fe--based pre-alloyed powder
Z2	C2	97.4	93.5	961	705	EMMM Fe-based pre-alloyed powder
X3	A3	99.6	106.5	1125	976	UPWA Co-based pre-alloyed powder
Y3	B3	99.3	104.3	1087	908	CWA Co-based pre-alloyed powder
Z3	C3	97.7	95.6	985	752	EMMM Co-based pre-alloyed powder

σ_b is the bending strength of blank matrix segments, and σ_d is the bending strength of matrix segments with diamond.

Table 5 Holding force coefficients of matrix to diamond

Segment number	Powder number	Bending strength		Q/%	F/%	Matrix powder type
		σ_b/MPa	σ_d/MPa			
X1	A1	964	825	14.42	85.58	UPWA Cu-based pre-alloyed powder
Y1	B1	942	776	17.62	82.38	CWA Cu-based pre-alloyed powder
Z1	C1	876	654	25.34	74.66	EMMM Cu-based pre-alloyed powder
X2	A2	1073	904	15.75	84.25	UPWA Fe-based pre-alloyed powder
Y2	B2	1032	838	18.80	81.20	CWA Fe--based pre-alloyed powder
Z2	C2	961	705	26.64	73.36	EMMM Fe-based pre-alloyed powder
X3	A3	1125	976	13.24	86.76	UPWA Co-based pre-alloyed powder
Y3	B3	1087	908	16.47	83.35	CWA Co-based pre-alloyed powder
Z3	C3	985	752	23.65	76.35	EMMM Co-based pre-alloyed powder

Table 6 Losing degree of diamond during sawing process

Segment number	Powder number	Diamond particles number	Diamond drop pits number	Losing degree of diamond/%	Matrix powder type
X1	A1	159	28	14.81	UPWA Cu-based pre-alloyed powder
Y1	B1	152	33	17.84	CWA Cu-based pre-alloyed powder
Z1	C1	135	48	26.23	EMMM Cu-based pre-alloyed powder
X2	A2	155	31	16.67	UPWA Fe-based pre-alloyed powder
Y2	B2	146	35	19.38	CWA Fe-based pre-alloyed powder
Z2	C2	134	50	27.17	EMMM Fe-based pre-alloyed powder
X3	A3	162	28	15.18	UPWA Co-based pre-alloyed powder
Y3	B3	156	32	17.02	CWA Co-based pre-alloyed powder
Z3	C3	140	45	24.32	EMMM Co-based pre-alloyed powder

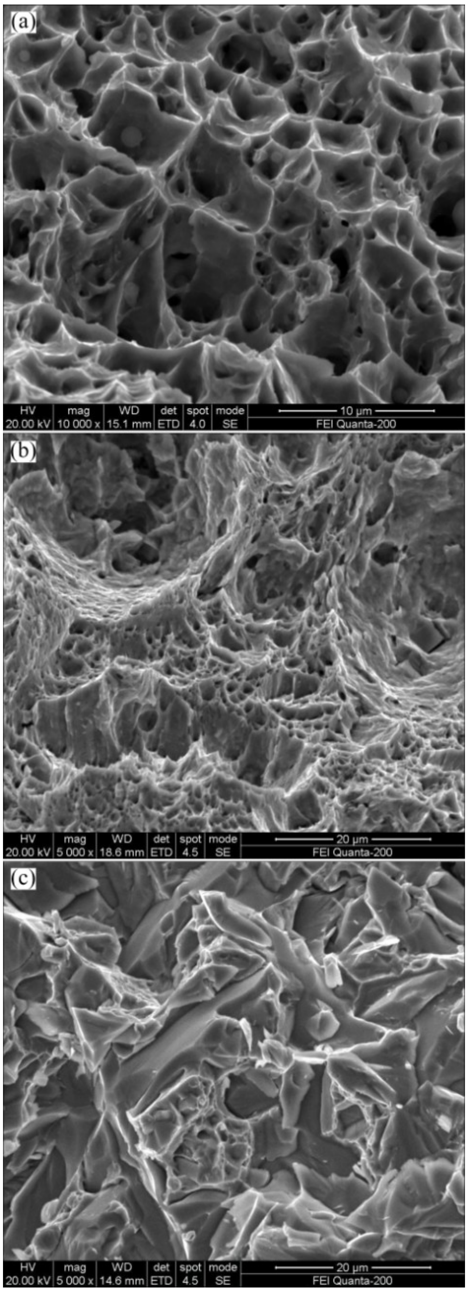

Fig. 2 Fracture morphologies of blank matrix sintered segments using Cu-based pre-alloyed powders prepared by UPWA (a), CWA (b) and EMMM (c)

powder also shows an improved holding ability to diamonds compared with the CWA powder.

3.4 Fracture analysis of diamonds matrix sintered segment

Figure 3 presents the fracture morphologies of the matrix sintered segments with diamonds using the Cu-based pre-alloyed powder prepared by UPWA, CWA and EMMM, respectively. In Fig. 3(a), no obvious gap is observed between diamond and the matrix material, revealing that the elements with strong carbide forming ability in the matrix material react with diamond in response. As a result, the bonding force is not only mechanical but also chemical. Thus, the holding ability of matrix material to diamonds is notably enhanced. The same phenomenon is also observed in Fig. 3(b). As can be seen in Fig. 3(c), the gap between diamond and matrix material is wide and continuous. The pit surface is dense and smooth. This phenomenon indicates that the bonding between the matrix and diamond is not chemical but mechanical. This indicates that the holding ability between the matrix material and diamonds is greatly increased by using the UPWA powder when compared with the EMMM powder.

4 Conclusions

1) The relative density, hardness and bending strength of matrix sintered segments prepared using the UPWA powder are greatly improved compared with those using the EMMM and CWA powders. The sintering temperature of the diamond tools is reduced as well as the diamond graphitization at high temperatures, when using the pre-alloyed powders, especially the UPWA powder. In addition, the mechanical properties of the diamond tools are also greatly improved.

2) Using the pre-alloyed powders, especially the UPWA powder, the holding force of matrix material to diamond is significantly improved.

3) The fracture of blank matrix sintered segments

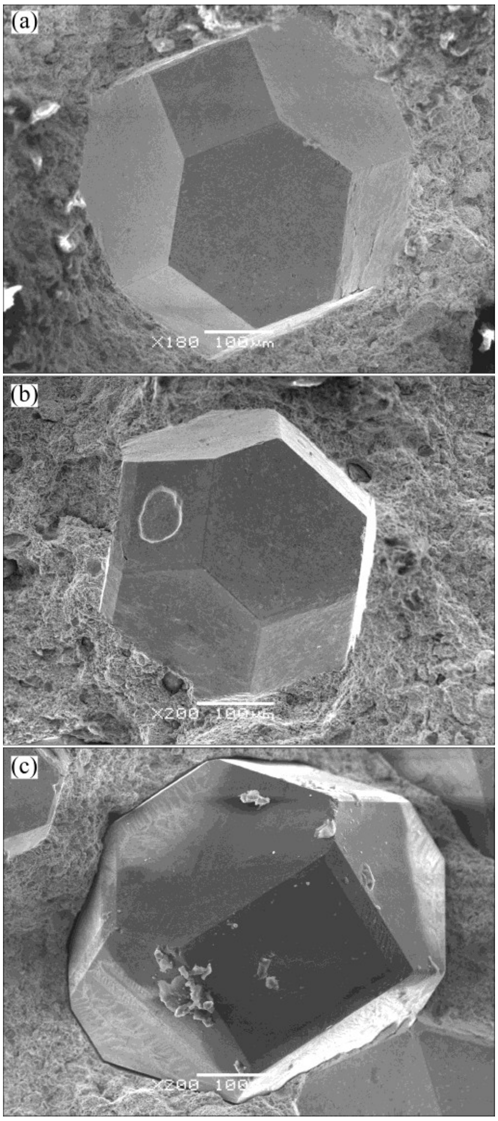

Fig. 3 Fracture morphologies of matrix sintered segments with diamond using Cu-based pre-alloyed powders prepared by UPWA (a), CWA (b) and EMMM (c)

using the pre-alloyed powder is ductile fracture and the morphology is fine. The UPWA powder has a much stronger ability than the EMMM powder in the holding performance to diamond. The UPWA powder also shows a certain improvement compared with the CWA powder.

4) The bonding force between matrix and diamond is not only mechanical but also chemical. The pit surface is dense and smooth, and the bonding between matrix and diamonds is not chemical but mechanical. The holding ability between matrix and diamond is greatly increased by using the UPWA powder when compared with the EMMM powder.

References

[1] ROMANKI A. Factors affecting diamond retention in powder metallurgy diamond tools [J]. Archives of Metallurgy and Materials, 2010, 55(4): 1073−1081.

[2] DAI He, WANG Li-min, ZHANG Jing-guo, LIU Yi-bo, WANG Yue-fa, WANG Lei, WAN Xin-liang. Iron based partially pre-alloyed powders as matrix materials for diamond tools [J]. Powder Metallurgy, 2015, 58(2): 83−86.

[3] ROMANSKI A, KOMSTANTY J. Ball-milled Fe−Ni and Fe−Mn matrix powders for sintered diamond tools [J]. Archives of Metallurgy and Materials, 2014, 59(1): 189−193.

[4] DONG Shu-shan, LIU Xiao-xu, LI Chang-qing, LIU Yi-qang. Analysis on domestic situation and development trend of pre-alloyed metal powder for diamond tools in China [J]. Superhard Material Engineering, 2012, 24(1): 43−47. (in Chinese)

[5] XIE De-long, WEN Jian-jie, FANG Xiao-hu, WAN Long. Current situation and expectation of the superhard material products [J]. Superhard Material Engineering, 2014, 26(1): 39−42. (in Chinese)

[6] QU Ming. Current Situation and future development of superhard material industry [J]. Superhard Material Engineering, 2015, 27(1): 39−41. (in Chinese)

[7] DING X, JARFORS A E W, LIM G C, SHAW K C, LIU Y C, TANG L J. A study of the cutting performance of poly-crystalline oxygen free copper with single crystalline diamond micro-tools [J]. Precision Engineering, 2012, 36(1): 141−152.

[8] PARK H K, ONIKURA H, OHNISHI O, SHARIFUDDIN A. Development of micro-diamond tools through electroless composite plating and investigation into micro-machining characteristics [J]. Precision Engineering, 2010, 34(3): 376−386.

[9] OLIVEIRA L J, BOBROVNITCHII G S, FILGUEIRA M. Processing and characterization of impregnated diamond cutting tools using a ferrous metal matrix [J]. International Journal of Refractory Metals and Hard Materials, 2007, 25(4): 328−335.

[10] ARTIN C, MUOLO M L, PASSERONE A. Diamond-metal interfaces in cutting tools: A review [J]. Journal of Materials Science, 2012, 47(7): 3252−3264.

[11] CLARK I E, KAMPGUIS B J. Cobalite HDR—A new prealloyed matrix powder for diamond construction tools [J]. Industrial Diamond Review, 2002, 62: 177−182.

[12] EUROLUNGSTENE. Keen—A concept in prealloyed powders [J]. Industrial Diamond Review, 2006, 3: 45−47.

[13] XIE Zhi-gang, QIN Hai-ging, LIU Xin-yu, WANG Jin-bao, JIANG Jian-feng. Study on the preparation of the prealloyed powder and its application for diamond tools [J]. Journal of Materials Engineering, 2011(3): 2−7. (in Chinese)

[14] BERTJAN K, ANJA S. Cobalite and nickel free bond powder for diamond tools: Cobalite CNF [J]. Industrial Diamond Review, 2004(1): 26−32.

[15] XU Hao-xiang, MA Hong-qiu, LUO Xi-yu. Atomized prealloyed powders and its application in diamond tool [J]. Diamond and Abrasives Engineering, 2004(1): 45−48. (in Chinese)

[16] SHEN Xiang, YAO Jiong-bing, MA Hong-qiu, LIU Yi-bo, LUO Xi-yu. Study on properties of water atomized Cu−Sn alloy powder [J]. Diamond and Abrasives Engineering, 2015, 35(4): 52−56. (in Chinese)

[17] ZHAO Wen-dong, XU Jun, SONG Yue-qing, LUO Ji, GUO Zhi-meng. Study on superfine pre-alloying powder for diamond tools by co-precipitation-decomposition method [J]. Powder Metallurgy Technology, 2010, 28(2): 130−135. (in Chinese)

[18] DONG Shu-shan, ZHOU Xiao-yan, DONG Xiao-lei, JIANG Bin, HOU Jun-yan. Current development, application situation and existing problems of the water atomized pre-alloyed metal used for diamond tools [J]. Superhard Material Engineering, 2013, 25(6): 47−52. (in Chinese)

[19] CHU Zhi-qiang, GUO Xue-yi, ZHANG Li, LIU Dong-hua. Effect of super high pressure water atomization parameters on diameter and micrograph of diamond matrix prealloy powders [J]. Materials

Science and Eingineering of Powder Metallurgy, 2015, 20(5): 808−814. (in Chinese)

[20] LI Wen-sheng, ZHANG Jie, WANG Shu-cai, DONG Hong-feng, LI Ya-ming, LIU Yi. Characterizations and mechanical properties of impregnated diamond segment using Cu−Fe−Co metal matrix [J]. Rare Metals, 2012, 31(1): 81−87. (in Chinese)

[21] TURCHETTA S. Cutting force and diamond tool wear in stone machining [J]. The International Journal of Adanced Manfacturing Technology, 2012, 61(5−8): 441−448.

[22] LUCIANO J O, GUEROLD S B. Processing and characterization of impregnated diamond cutting tools using a ferrous metal matrix [J]. International Journal of Refractory Metals and Hard Materials, 2007, 25(4): 328−335.

[23] DING Tian-ran, LONG Wei-min, ZHANG Hai-yan. Effect of oxygen content on mechanical properties of diamond tool matrix [J]. Welding and Joining, 2013(1): 42−44. (in Chinese)

[24] XIANG Bo. Preparation and property of pre-alloyed powder in diamond tools [D]. Changsha: Central South University, 2007: 43−44. (in Chinese)

[25] SHI Dong-mei, YANG Kai-hua, PAN Bing-sun. Calculation of diamonds distribution on segments working face and cutting thickness of single diamond [J]. Tools Technology, 2002, 36(5): 7−10. (in Chinese)

[26] POLINI W, TURCHETTA S. Evaluation of the diamond tool wear [J]. The International Journal of Adanced Manfacturing Technology, 2005, 26(9): 959−964.

超高压水雾化制备预合金粉末在金刚石工具中的应用

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摘　要：采用超高压水雾化工艺制备金刚石工具用铜基、铁基、钴基预合金粉末，并对超高压水雾化法、常规水雾化法以及单质金属机械混合粉末制备的金刚石工具烧结节块的力学性能、胎体对金刚石的把持力、空白与含金刚石胎体烧结节块的断口形貌进行测定、比较与分析。结果表明：超高压水雾化预合金粉末烧结节块的相对密度、硬度和抗弯强度等力学性能有显著提高。超高压水雾化预合金粉末烧结节块断口形貌为韧性断裂，预合金粉末与金刚石之间除具有机械嵌镶力外，还存在化学结合力，胎体粉末材料对金刚石的把持能力明显增强。采用超高压水雾化预合金粉末可大大改善金刚石制品胎体的力学性能与使用寿命。

关键词：超高压水雾化；预合金粉末；金刚石工具；烧结节块

(Edited by Sai-qian YUAN)