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ARTICLE

Microstructure and Mechanical Properties of PDC Cutters Vacuum Brazed by AgCuInTi Filler Metal

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Abstract: Polycrystalline diamond compact (PDC) cutters and carbon steel were brazed by AgCuInTi filler metal under vacuum condition. The effects of brazing temperature on the wettability of base metal and shear strength of joints were investigated. Besides, the joint's interface microstructure, composition, and phases were analyzed. Results show that the AgCuInTi filler metal exerts a good wetting effect to the surface of cemented carbide and steel. With the increase in brazing temperature, the wetting angle decreases and the spreading area increases. The suitable temperature for vacuum brazing of PDC cutters is 770 °C, and the maximum shear strength is 228 MPa at this temperature.

Key words: PDC cutter; vacuum brazing; brazing temperature; shear strength; microstructure

1 Introduction

Polycrystalline diamond compact (PDC) bits are the dominant tools employed in the drilling industry, and the wide application has brought about great economic benefits[1–2]. As the most important cutting unit of drill bit, PDC cutters are used for breaking rock and coal, and the performance largely determines the drilling effect and service life of drill bits. PDC cutter consists of diamond and hard alloy steel. The brazing of diamond and hard alloy steel is a key process in the manufacturing process of the drill bit. Currently, the main production process of PDC cutters is flame brazing. This method is difficult to control the consistency of product quality, and the high flame temperature will deteriorate the properties of PDC cutters, especially the wear resistance. In addition, its production efficiency is low. There are higher requirements for operators, and the labor intensity of workers is large. The vacuum brazing process has been widely used in the welding of cutting tools due to the advantages of uniform heating, nonoxidative technique, and no need for flux[3]. Thus, using vacuum protection is an appropriate way to reduce the polycrystalline diamond oxidation. At the same time, automated vacuum brazing is used instead of the original manual flame brazing to improve the quality of the product, productivity, and work environment.

Due to the attractive advantages of vacuum brazing, the vacuum brazing process of PDC cutters was investigated in this research. PDC cutters usually consist of a polycrystalline diamond layer and a cemented carbide substrate, so the essence of brazing is the connection between the cemented

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carbide and steel. During the brazing process, increasing the brazing temperature can promote the wetting and spreading of liquid solder. However, it can also deteriorate the polycrystalline diamond layer by the thermal damage. So the key point is to find a balance between high connection strength and minimal thermal damage for PDC cutters. Therefore, joints fabricated by cemented carbides and steel should be further investigated.

Extensive research has been conducted to optimize brazing parameters and to improve the properties of joints made by cemented carbide and steel using Cu-, Ni-, and Ag-based filler metals[4–8]. YG18 cemented carbide and 40Cr steel were joined with Ag-Cu-Ti filler metal[3], and it was found that Ti and C atoms formed a continuous TiC layer. At the same time, with the increase in brazing temperature, the bonding strength is initially increased and then decreased. Amelzadeh et al[9] fabricated a joint using a Cu/Ni double-layer filler metal, and revealed the effects of holding time on the microstructure and mechanical properties of the joints. Then, an Ag-Cu-Zn-Cd alloy was used as filler metal to braze the cemented carbide/ Cr-Mn steel joints, and it was proved that the shear strength and hardness of the brazed joints were increased with the increase in Cu-rich phase[10]. Barrenan et al[11] found that the residual stresses caused by the thermal expansion mismatch between WC-10Co and steel severely deteriorated the mechanical properties of the joints. Wang et al[12] investigated the microstructure and mechanical properties of YG8/IN718 joint with AgCuNiLi alloy as filler, and observed that a fracture occurred in the interlayer. The abovementioned research is about the dissimilar joining between cemented carbide and steel without considering the thermal damage of the polycrystalline diamond layer, so the brazing temperature is usually high (above 850 °C). Galli et al[13] revealed that the additive of In can improve the wetting behavior and decrease the brazing temperature. Akselsen et al[14] found that the AgCuTi solder with a small amount of In, Sn, and other elements will reduce the saturation of Ti in the Ag-Cu matrix. The low surface energy of In will promote the separation of Ti and the Ag-Cu matrix, thus improving the activity of element Ti. In addition, AgCuInTi filler has been widely used for brazing ceramics with ceramics[15–16] or ceramics with metals[17–20].

According to the abovementioned information, considering the wetting effect and the strength as well as non-toxicity, titanium and indium were selected to be added into the silver and copper filler metal. In addition, the weldability of diamond is not very good. The linear expansion coefficient of diamond is lower than that of most metals, so a crack will be formed in the diamond under the action of thermal stress. At the same time, diamond is prone to graphitization at high temperatures, and once it is graphitized, it is difficult to braze any more. Therefore, it is important to set an appropriate temperature to obtain satisfactory joints.

Based on the abovementioned understanding, wetting is controlled by many parameters. Brazing temperature is one of the wettability parameters, which affects not only the fluidity and characteristics of filler alloy, but also the properties of PDC cutters. Hence, in this research, the effects of brazing temperature on the shear strength and microstructure of joints made by PDC cutters and carbon steel with AgCuInTi as filler metal were investigated.

2 Experiment

In this study, PDC cutters were made by YG8 cemented carbide with the dimension of Φ13.44 mm×4.5 mm and the carbon steel (the carbon content is about 0.5wt%) with the dimension of Φ15 mm×30 mm. The Ag59Cu23In15Ti3 alloy was used as filler metal. The oxide layer on the surface of both the cemented carbide and the steel was removed with a diamond grinding wheel and SiC sandpaper. Ultrasound and alcohol were used to clean the welding surface before the tests. For the joining process, the specimens were placed under the pressure of about 1 MPa in the vacuum furnace of 1.33×10^{-3} Pa, and the brazing temperature was 730−770 °C. The pressure was applied on the joint to fix and promote bonding. The heating rate was 10 °C/min and the holding time was 20 min. After the brazing process, three specimens were tested for strength and one specimen was cut for the diamond cutting tool. All specimens were mounted and prepared for the polishing. The shear strength test was conducted by the universal Instron machine and the principle diagram of shear test is shown in Fig.1.

Wettability test was conducted by the sessile drop test. After preparing the surfaces, AgCuInTi filler alloy was placed on the surface of both YG8 cemented carbide and carbon steel, and it was heated by a specific method according to the brazing process.

3 Results and Discussion

3.1 Wettability

Fig.2 shows the spread morphologies of the joints at YG8 cemented carbide side and carbon steel side brazed at different temperatures after wettability test. At 730 °C, the solder spreads in an oval shape on both sides, as shown in Fig.2a and 2e. However, a passivation film is formed on the surface of the solder, which may be due to the small wetting force of solder. When the temperature increases, the solder spreads in a square shape and the surface is bright on the YG8 cemented carbide side, as shown in Fig.2b–2d. However, with the increase in the brazing temperature from 740 °C to 770 °C, the spread shape of the solder exhibits significant changes

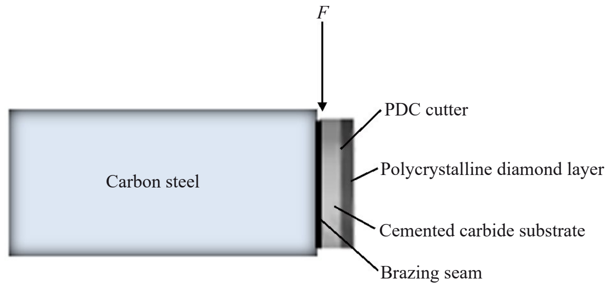

Fig.1 Schematic diagram of shear test for brazing joint

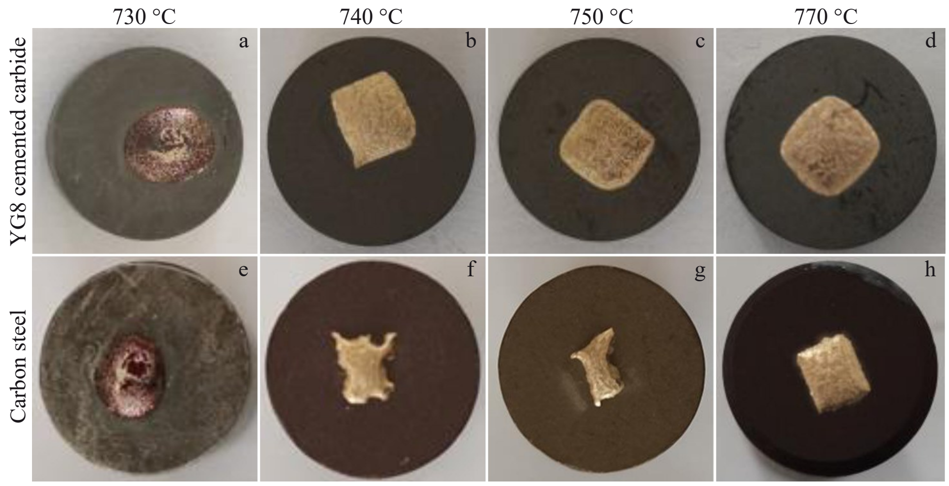

Fig.2 Spread morphologies of joints at YG8 cemented carbide side (a–d) and carbon steel side (e–h) brazed at different temperatures after wettability test: (a, e) 730 °C; (b, f) 740 °C; (c, g) 750 °C; (d, h) 770 °C

from an irregular shape to a square shape on the carbon steel side, as shown in Fig. 2f–2h. It may be related to the solder shape and the coverage area of the solder used in the test. This result indicates that the solder spreads well on both sides when the brazing temperature is 770 °C, as shown in Fig. 2d and 2h.

Fig. 3 and Fig. 4 show the average wetting angles and the spreading areas on both sides of the joint brazed at different temperatures, respectively. The average wetting angles of both sides are decreased with the increase in brazing temperature. The solid contact angle for the liquid braze is less than 90° on the surfaces of both YG8 cemented carbide and the carbon steel, indicating that they can be wetted[21]. By increasing the brazing temperature, the spreading areas on the YG8 cemented carbide side increase. Particularly, when the brazing temperature is higher than 740 °C, the spreading area increases rapidly, as shown in Fig. 4. However, the spreading areas on the carbon steel side increase slowly. It is shown that the liquid filler metal has more opportunities to wet the surface of YG8 cemented carbide. Meanwhile, the spreading areas on YG8 cemented carbide side are larger than those of carbon steel side. Thus, according to these results, it is clear that a suitable wetting state of the YG8 cemented carbide and the carbon steel is achievable by the AgCuInTi filler metal.

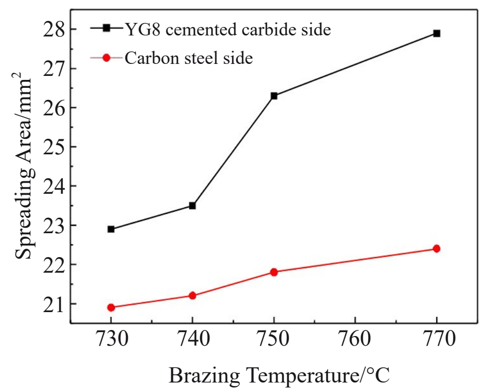

Fig.4 Spreading area of joints brazed at different temperatures

3.2 Mechanical properties

The results of the shear test of the brazed joints are represented in Fig. 5. According to Fig. 5, with the increase in the brazing temperature, the shear strength of the joints increases. It can be observed that a certain temperature is necessary to promote the diffusive phenomena. By further increasing the brazing temperature, the opportunity for element diffusion occurs. When the brazing temperature is

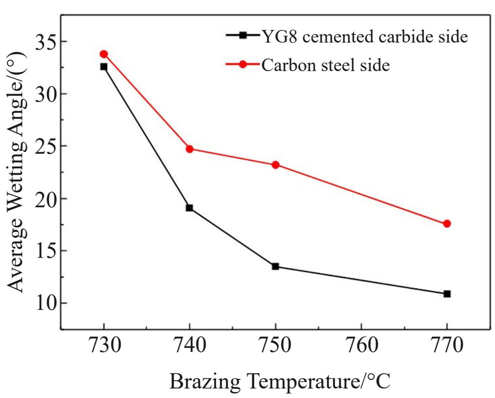

Fig.3 Average wetting angle of joints brazed at different temperatures

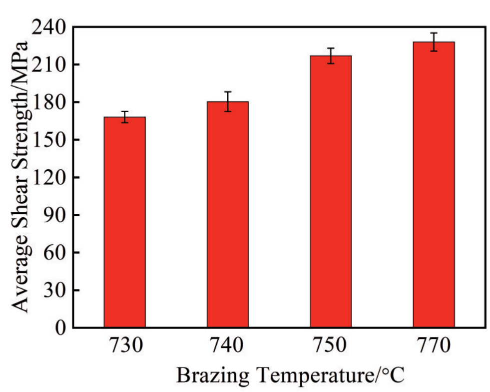

Fig.5 Average shear strength of joints brazed at different temperatures

below 750 °C, the shear strength of the joint is less than 200 MPa; when the brazing temperature is above 750 °C, the shear strength of the joint is more than 200 MPa. Therefore, the maximum shear strength of the joint (228 MPa) is achieved when the brazing temperature is 770 °C. This result is related to the good spread shape, small wetting angles, and big spread areas, as shown in Fig.2–Fig.4. As a result, the shear strength increases by about 60 MPa[22] by increasing the brazing temperature from 730 °C to 770 °C.

There are some elements (Ti and In) to improve the strength. Element In can not only decrease the temperature, but also improve the strength and abrasion resistance. Atom In has a larger atomic size than atom Ti, and it can form replacement solid solution in silver filler metal, which will disturb the regularity of the arrangement of the surrounding solvent atoms within a certain range, and cause the elastic lattice distortion. Therefore, the Cottrell gas mass forms, which hinders the dislocation slip and improves the strength of the joint. But when the brazing temperature is high, the size of the grains may increase, which may decrease the strength.

3.3 Microstructure characterization

Fig. 6 shows the interface microstructures of joints between YG8 cemented carbide and carbon steel brazed at 730–770 °C. At the brazing temperature of 730 °C, the thickness of brazing joints is about 280 μm, and there are several band-like structures in the brazing joints. The appearance of band-like structure leads to the heterogeneous distribution of the solder, which prevents the full diffusion of elements. Therefore, low temperature will not provide a complete wetting process, since it leads to an imperfect joint, and the shear strength is low, as shown in Fig. 5. According to the previous research, when the brazing temperature is 720 °C, some undiffused Ti atoms are still in the middle of the filler, which may react with Cu and In in the AgCuIn eutectic to form the Cu_2InTi phase[19]. With the increase in brazing temperature to 740, 750, and 770 °C, the thickness of brazing joints is about 220, 174, and 184 μm, respectively. The band-like structure becomes wider, and the whole brazing joint shows an island-like eutectic structure. It is apparent that the AgCuInTi filler alloy is well bonded to the base materials, especially when the brazing temperature is 750 and 770 °C. The brazing joints spread evenly and the solid solution is better. So the strength also increases with the decrease in the thickness of brazing joints. As the elements gradually diffuse, the thickness of the brazing joint reduces when the brazing temperature is above 750 °C. Zhao et al[19] found that when the brazing temperature further increased to 750 °C, the Cu_2InTi phase disappeared and Ti continued to diffuse. It seems that this phase significantly affects the mechanical properties of the brazing joints. When the brazing temperature is 770 °C, the microstructure and the wettability, including the wetting angles and the spreading areas, are good. Therefore, a satisfactory brazing joint is obtained.

Concerning the microstructure characteristics of the transverse cross-sections of the joints, the chemical composition at different zones of the joint brazed at 770 °C was analyzed, as indicated by the marked points in Fig. 6d. The chemical composition is listed in Table 1. It can be seen that the upper part is the carbon steel and the lower part is the YG8 cemented carbide. According to chemical composition results, it can be speculated that point A (the light gray phase) at the center of the interface with the Ag content of 82.78at% should be essentially composed of Ag(s. s). Since the atomic content of Cu and Ti is approximately 1.5:1, the point B (dark black phase) may be mainly composed of Cu_3Ti_2. Similarly, the point C (light black phase) should consist of Cu_3Ti. Based on the Cu-Ag binary phase diagram[23], it is well-known that these two elements have a very low solubility. Therefore, a

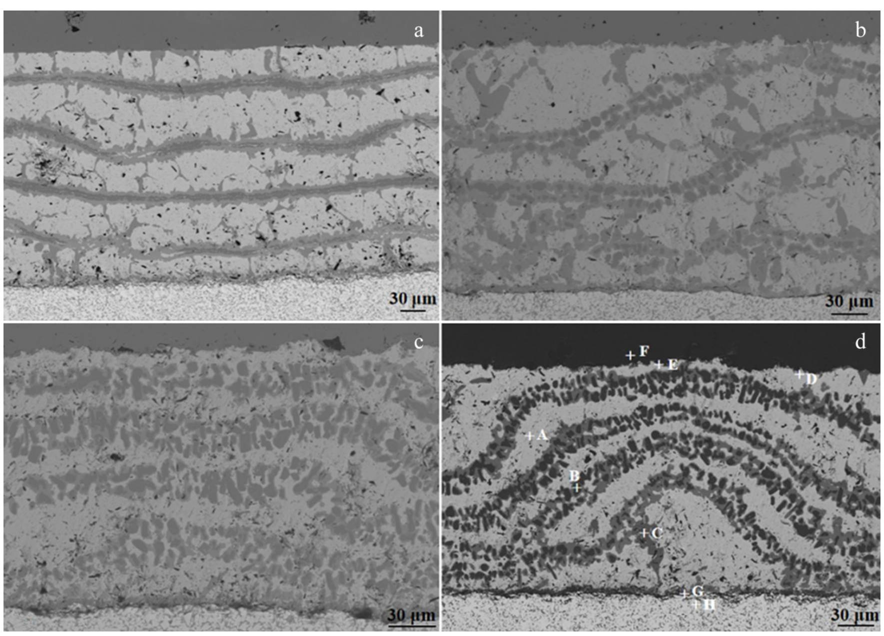

Fig.6 Interfacial microstructures of joints brazed at different temperatures: (a) 730 °C, (b) 740 °C, (c) 750 °C, and (d) 770 °C

Table 1 Chemical composition of points marked in Fig.6d (at%)

Point	C	Ti	Fe	Co	Cu	Ag	In	W
A	1.75	0.04	0.10	0.23	5.79	82.78	9.18	0.13
B	4.85	34.34	0.02	0.05	57.85	2.36	0.35	0.18
C	4.59	17.07	0.15	0.09	50.38	1.88	25.84	0.00
D	5.68	12.61	2.26	0.03	56.75	18.14	4.53	0.00
E	5.16	27.36	52.16	0.27	9.37	3.74	1.94	0.00
F	5.23	1.40	91.7	0.39	0.44	0.36	0.22	0.25
G	6.76	14.5	0.32	6.43	6.28	4.21	5.46	56.05
H	9.17	0.31	0.05	0.68	1.19	1.61	0.29	86.71

copper-rich phase Cu-Ti(s.s) is formed. The point D near the steel interface may be essentially composed of Cu_4Ti with a certain amount of Ag and a little In and Fe. Therefore, Ti and Cu with different atomic ratios form compounds and intermetallic compounds, and they are distributed within layers, which indicates that titanium has a good solid solubility in copper. So the brazing joint includes Ag(s.s) solid solution and Cu(s.s) solid solution. At the interface between the solder and the carbon steel, the point E is composed of Fe and Ti and their atomic ratio is approximately 2:1, which may indicate the existence of Fe_2Ti. The atomic ratio of Cu and Ti is approximately 1:3, so it is mainly composed of $CuTi_3$. This area also contains a small amount of Ag and In. Zheng et al[3] found that Ti atoms on the steel/filler metal side can combine with Fe atoms to form Fe_2Ti, which is consistent with the conclusion in this research. On the upper side of base metal, the point F mainly consists of Fe, and a small amount of Ti and C can also be detected. At the interface of the solder and YG8 cemented carbide, the point G may be composed of $CuTi_2$ with a large amount of W and a small amount of Ag, In, C, and Co. The point H mainly consists of W with a small amount of C. It is obvious that the interface on both sides is rich in Ti, such as points E and G. It can be seen that with the increase in temperature, the reaction between Ti and AgCuIn changes to the reaction between Ti and Cu or Fe and Ti, as shown in Table 1. Due to the formation of these products, the strength of the brazed joint increases.

3.4 Length distribution

The element distributions of the joint brazed at 730–770 °C are shown in Fig. 7. The upper part is the carbon steel and the lower part is the YG8 cemented carbide. According to the element diffusions of joint brazed at 730 °C, elements Ti and Cu exhibit a band-like structure in the bonding zone, which hinders the further diffusion of elements Ag and In. As the brazing temperature increases, the copper-rich phase Cu-Ti(s.s) grows further and it is distributed evenly throughout

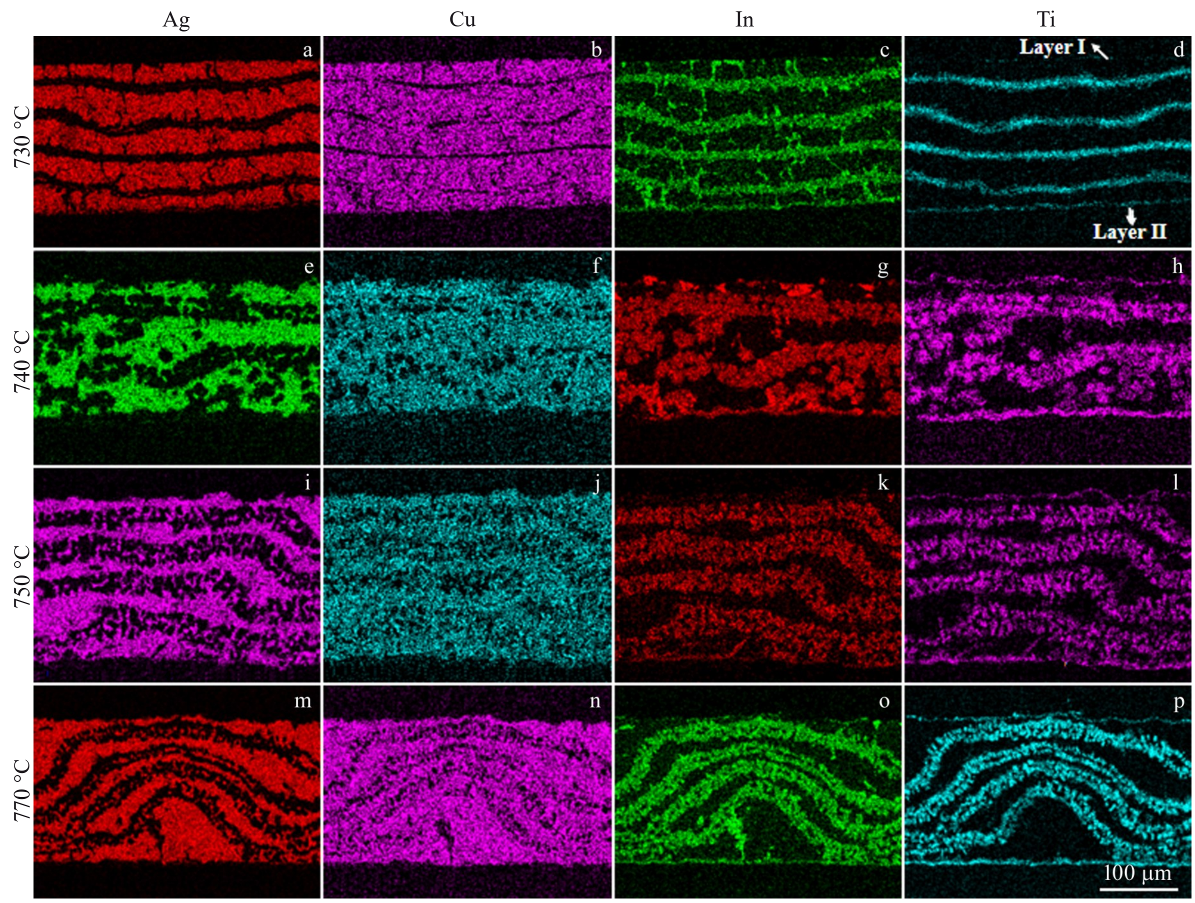

Fig.7 Element distributions of Ag (a, e, i, m), Cu (b, f, j, n), In (c, g, k, o), and Ti (d, h, l, p) across interface of joints brazed at different temperatures: (a–d) 730 °C, (e–h) 740 °C, (i–l) 750 °C, and (m–p) 770 °C

the brazing joint. The distribution patterns of elements Ag and In are basically the same: In and Ag are enriched at similar areas. In the process of diffusion, the Ag-based solid solution Ag(s. s) contains the element In. The distribution patterns of Cu and Ti are opposite to those of Ag and In.

It is worth noting that the reaction between solder and base metal leads to the aggregation of Ti atoms at the interface of both sides and preferentially on the YG8 cemented carbide side. The interface near the carbon steel and YG8 cemented carbide is remarked as Layer I and Layer II, respectively, as shown in Fig. 7d. When the brazing temperature is 730 °C, Layer I is so thin and discontinuous, and the thickness of Layer I and Layer II is about 0.2 and 0.7 μm, respectively. When the brazing temperature is 770 °C, the thickness of Layer I and Layer II is about 1.2 and 6.0 μm, as shown in Fig.7p. With the increase in brazing temperature, the interface reaction is enhanced and the reaction layers become thicker, clearer, and continuous. As the thickness of the reaction layer increases, the strength of the joint increases. It can be seen that the strength of the joint brazed at 770 °C is larger than that at 730 °C. Layer I is thinner than Layer II due to the large percentage of carbon in the YG8 cemented carbide. Ref. [3] reported that by increasing the brazing temperature, WC grains become coarser, and C atoms diffuse to the interface between the cemented carbide and the filler metal. A thin TiC layer is formed between elements Ti and C due to the strong affinity effect. Negative Gibbs free energies (ΔG^0, kJ/mol) promote chemical reactions. TiC formed by Ti+C→TiC reaction can be studied based on the thermodynamic calculation[24] of $\Delta G^0 = -184.8 + 12.55\times10^{-3}T$, where T is the temperature.

The formation of metal bond between PDC cutters and carbon steel filler mainly depends on the interface reaction. Guo et al[25] also found that the formation of TiC layer at the interface of the steel and the filler metal can prevent the diffusion of Fe and the formation of hard-brittle phase. The diffusion of copper is the same as that of titanium. The reaction between Ti and Cu at the interface forms some compounds, such as $CuTi_3$ and $CuTi_2$. Kvryan et al[26] reported that Ti atoms diffused to the interface and preferentially reacted with Cu atoms from the braze, which resulted in obvious silver segregation to the interface center. Therefore, on the one hand, element Ti can react with the elements in the solder to form compounds and change the microstructure. On the other hand, element Ti can participate in the interface reaction and enhance the diffusion of elements at the interface to achieve a reliable connection. The formation of TiC can reduce the stress of the joint and improve the bonding strength of the brazed joints.

Based on the abovementioned results, the bonding mechanism of the joint is studied, and Fig. 8a–8d show the microstructure evolution. When the temperature rises to the melting temperature of the AgCuInTi metal filler, the surface of the substrate is wetted by the molten filler. Simultaneously, the elements Ag, Cu, In, Ti, Fe, W, C, and Co begin to diffuse. Partial Ti atoms form the compounds with the element Cu and

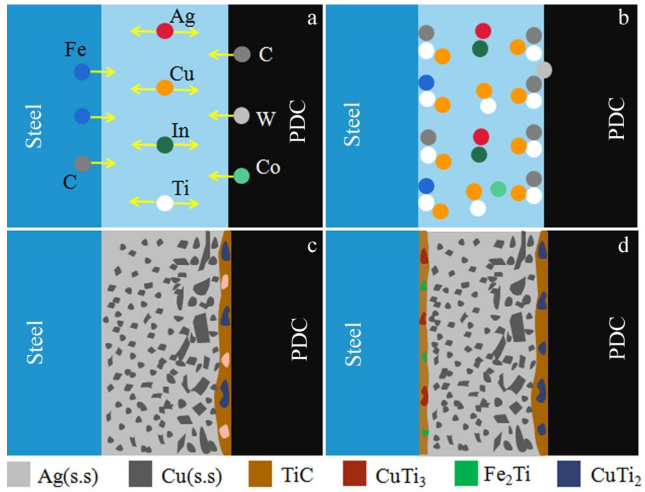

Fig.8 Schematic diagrams of microstructure evolution of joint between PDC cutters and carbon steel

are distributed in the brazing seam; other Ti atoms are diffused to both sides of the base materials to form a TiC layer. Some Cu atoms are aggregated around the Ti atoms to form $CuTi_3$ and $CuTi_2$ near the interface. A certain number of Fe atoms near the carbon steel combine with Ti to form Fe_2Ti, and then Ag(s.s) and Cu(s.s) remain in the middle of the brazing seam. Therefore, the typical microstructure of joints between the PDC cutters and carbon steel brazed by AgCuInTi filler metal is carbon steel/Fe_2Ti/TiC/$CuTi_3$/Ag-In(s. s)+Cu-Ti(s. s)/$CuTi_2$/TiC/YG8 cemented carbide.

3.5 Morphology and phase of fracture surface

The fracture morphologies of joint brazed at 730 °C are shown in Fig. 9. Regions I and II are marked in Fig. 9a. The fracture mainly presents a river-like pattern, but dimples cannot be observed, which indicates that at the low brazing

Fig.9 Fracture morphologies of joints brazed at 730 °C: (a) appearance, (b) magnified image of region I, and (c–d) magnified images of region II marked in Fig.9a

temperature, a satisfactory joint cannot be obtained. So the strength of the joint brazed at 730 °C is the lowest.

The fracture morphologies of joint brazed at 770 °C are shown in Fig.10. Regions I, II, and III are marked in Fig.10a. There are three zones. Region I (Fig.10b) mainly contains Cu (35.23%), Ag (29.43%), Ti (15.23%), and In (12.74%). This area presents obvious cleavage fracture. As shown in Fig.10c, region II mainly consists of Ag (60.91%), Cu (20.06%), In (9.97%), a little Ti (1.83%), and a little C (6.21%). Though this area shows cleavage fracture, a few dimples can be observed. As the shear force increases gradually, Fig. 10d (region III) exhibits a typical brittle characteristic. This area mainly consists of W (59.41%), Co (12.17%), C (11.34%), as well as a little Ag, Cu, In, and Ti. The results show that the fracture mechanism of the joint is cleavage fracture.

The phases of the fracture surfaces were identified by XRD, and the results are shown in Fig.11. According to Fig.11, there are the solid solution of Ag, Cu_3Ti_2, TiC, and WC on the fracture surface. Combined with the chemical composition analysis in Table 1, Ag(s.s) and Cu_3Ti_2 intermetallic compound can be detected at the fracture surfaces, which can further prove that the fracture occurs in the core interlayer. When the brazing temperature is low (about 720 °C), the joint exhibits a fully brittle characteristic due to the heterogeneous distribution of the solder. When the brazing temperature is high (800 °C), the fracture of joints also shows a fully brittle characteristic due to the large grains. Therefore, under the current experimental conditions, 770 °C is a reasonable temperature.

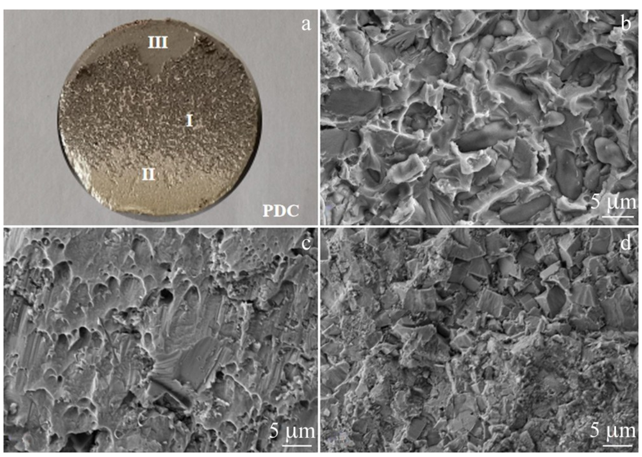

Fig.10 Fracture morphologies of joints brazed at 770 °C: (a) appearance, (b) magnified image of region I, (c) magnified image of region II, and (d) magnified image of region III marked in Fig.10a

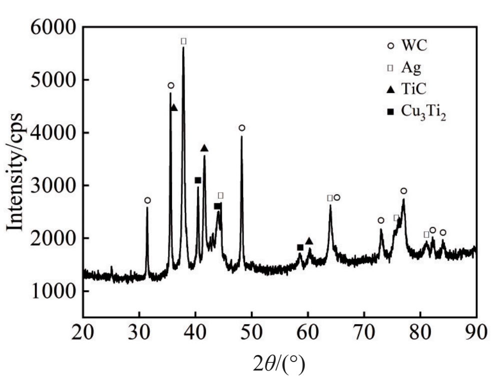

Fig.11 XRD pattern of fracture surface of joint brazed at 770 °C

4 Conclusions

1) The AgCuInTi filler metal exerts a good wetting effect to the surface of both YG8 cemented carbide and carbon steel. By increasing the brazing temperature, the wetting angle decreases, whereas the spreading area increases.

2) The strength of the joint increases with the increase in brazing temperature. The suitable temperature for vacuum brazing of PDC cutter is 770 °C, and its maximum shear strength is 228 MPa.

3) The AgCuInTi filler alloy can be well bonded with YG8 cemented carbide and carbon steel when the brazing temperature is above 750 °C. Ti can react with Cu, Fe, C, and other elements. The reaction enhances the element diffusion at the interface and achieves reliable connection.

4) The failure shows a cleavage fracture mechanism and the solid solution of Ag(s.s) and Cu_3Ti_2 observed on the fracture surface prove that the fracture occurs in the core interlayer.

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AgCuInTi真空钎焊金刚石复合刀具的组织与力学性能

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摘　要：在真空条件下，采用AgCuInTi钎料焊接金刚石复合刀片和碳钢，研究了钎焊温度对母材润湿性和接头抗剪切强度的影响。同时，对接头的界面组织、成分和物相进行了分析。结果表明，AgCuInTi钎料对硬质合金和钢的表面具有良好的润湿作用。随着钎焊温度的升高，润湿角减小，扩散面积增大。真空钎焊金刚石复合刀片的适宜温度为770 ℃，该温度下的最大抗剪切强度为228 MPa。

关键词：金刚石复合刀片；真空钎焊；钎焊温度；抗剪切强度；微观结构

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