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Residual stress distribution in synthetic diamond grains brazed with Ni-Cr brazing filler metal

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ABSTRACT

The distribution of residual stress in three different directions of synthetic diamond grains brazed with Ni-Cr brazing filler metal having different embedding depth was measured by Raman spectroscopy to investigate the influence of embedding depth on residual stress of diamond-metal joints and optimize the embedding depth of synthetic diamond grains in brazed synthetic diamond tools. The results show that the residual stress is stable without remarkable gradient in the core zones of brazed synthetic diamond grains. However, in the region of both end of central axis, the margin region of the central plane and the margin region of the section plane between the brazed synthetic diamond grains and the surface of Ni-Cr brazing filler metal, the stress distribution gradient is rather great. The maximum tensile stress always exists in the margin region of the section plane and it has the most important effect on the mechanical property of brazed synthetic diamond grains. The embedding depth of synthetic diamond grains in brazed synthetic diamond tools is optimized at 40–50% based on the maximum tensile stress and the requirement of machining process.

Keywords: residual stress; synthetic diamond; Ni-Cr brazing filler metals

1. INTRODUCTION

Compared with the conventional electroplated diamond tools and sintered diamond tools, brazed diamond tools have the advantages of high grains protrusion and strong bond by virtue of chemical and metallurgical reaction among the parts of diamond grains, brazing filler metals and tools substrate at elevated temperature [1, 2]. Brazed diamond tools are widely used in the field of grinding hard-brittle materials, such as engineering ceramic [3], concrete [4], metal-matrix composites [5] and super-alloys [6], and have attracted much attention from relevant experts and manufactures to study and develop in recent years.

Due to the mismatch of thermal expansion coefficients among the parts of brittle diamond grains, ductile brazing filler metals and steel substrate, which will case large residual stress in brazed diamond grains after brazing [7–10]. Just like the quality of utilized diamond grains and the properties of brazing filler metals, the stress distribution in brazed diamond grains has an impact on the lifetimes of brazed diamond tools. Larger stress in brazed diamond grains will result in the diamond grains to fracture or fall off from the tools substrate, which reduces the tool's lifetime. There are many studies on the residual stress in brazed ultra-hard material tools. CHEN *et al.* [11] have studied the residual stress in diamond/steel joints with finite element, the larger stress is the mainly factor of crock in synthetic diamond grains, even though the simulated stresses are larger than Raman spectroscopy stresses, the simulated stresses and Raman spectroscopy stresses have similar trends. AKBARI *et al.* [12] have investigated the residual stresses in brazed diamond metal joints using Raman spectroscopy and finite element simulation, the computational and experimental peak shift values were fairly close to each other, and the TiC interlayer in simulation is very important. DING *et al.* [13–18] have studied the stress characteristics, the relationship between embedding depth and residual stress in the cBN grains of mono-layer brazed abrasive tools and the grinding performance of mono-layer brazed cBN wheel, the maximum stress exits in the interface between brazing filling metal and cBN grains, meanwhile, it has the most important influence on the mechanical property of cBN grains, the embedding depth of cBN grains in filler alloy is optimized at 30–40% of the total height of cBN grains according to the stress distribution and the grinding performance.

Many factors have an impact on the stress intensity and stress distribution in brazed diamond grains, such as the brazing technology parameters [9], material performance [10, 11] and the embedding depth (the distance

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between the bottom of synthetic diamond grains and the surface of brazing filler metals). If the embedding depth is too large, the chip storage space is insufficient and the grinding ability of brazed diamond tools is imperfect. Oppositely, if the embedding depth is very small, fracture and cracking could occur in diamond grains even though very strong bond is realized between diamond grains and brazing filler metals during brazing process [7, 8]. So, it is very difficult to determine the embedding depth of diamond grains in brazed diamond tools during the fabrication of brazed diamond tools. All factors need to take synthetically into account, such as mechanical properties, chip storage space and bonding strength. In this work, the aim is to study the distribution of residual stress in synthetic diamond grains brazed with Ni-Cr brazed filler metals, and optimize the embedding depth of synthetic diamond grains in Ni-Cr brazed filler metals according to the stress distribution in brazed synthetic diamond grains and the grinding performance of brazed synthetic diamond tools.

2. MATERIALS AND METHODS

2.1. Materials

Generally, it is difficult to determinate the uniform shape of diamond grains for the sharp edges and corners of synthetic diamond grains. According to the different synthetic conditions, the crystal shape of synthetic diamond can be divided into octahedron, cube and cube-octahedron polyform, etc., cube-octahedron polyform is the most common. In this work, the morphology of synthetic diamond grains is considered as cube-octahedron with diameter about 0.2 mm, which was purchased from Zhongnan Diamond Co. LTD; Ni-Cr alloy (from Beijing general research institute of mining & metallurgy) is utilized as the brazing filler metals, the specific composition of Ni-Cr brazing filler metals is shown in Table 1. The tools substrate is cylindrical Q235A steel (chemical elements: C 0.2%, Mn 0.45%, S 0.05%, P 0.04%, Si 0.3%) with diameter of 20 mm and height of 10 mm.

2.2. Experiment

Before brazing, synthetic diamond grains and Q235A steel substrate were cleaned by ultrasound in acetone for five minutes, then, drying in the air. Figure 1 shows the schematic showing of brazed synthetic diamond grains specimen. First, synthetic diamond grains were placed in the top layer of Ni-Cr brazing filler metals, and then synthetic diamond grains, Ni-Cr brazing filler metals and tools substrate Q235A steel were joined together by chemical reaction in protective atmosphere furnace with heating temperature 1050 °C and brazing time 5 minutes. Argon was utilized as protective atmosphere. According to synthetic diamond grains size and the surface area of Q235A steel substrate, different weight of Ni-Cr brazing filler metals is weighed, and then the embedding depth of diamond grains from 20% to 80% was controlled by adjusting the thickness of Ni-Cr brazing filler metals. During the brazing process, the heating and cooling rate was controlled as 10 °C/min, which is very small and could form uniform temperature fields in specimens, so the stress arising from the temperature variation of synthetic diamond grains, Ni-Cr brazing filler metals and Q235A steel substrate was very small and neglected.

2.3. Residual stress measurement

Due to synthetic diamond grain is sp3 hybridization structure and the size is very small, the conventional stress measurement techniques, such as strain resistance gauges and X-ray diffraction, are not able to measure the residual stress of the brazed synthetic diamond grains, especially in the selected region. In this work, Raman spectroscopy was used to measure the residual stresses in brazed synthetic diamond grains with different embedding depth along three different directions. The central axis of synthetic diamond grains, that is, line I in Figure 1. The radial direction along the horizontal axis in the central plane of synthetic diamond grains, that is, line II in Figure 1. The radial direction along the horizontal axis in the section plane between brazed synthetic diamond grains and the top of Ni-Cr brazing filler metals, that is, line III in Figure 1. According to the distribution characteristics of the residual stress in brazed brittle materials, such as SiC, cBN, ceramics, the three directions in brazed synthetic diamond grains are always the regions of the maximum stress exits [13]. The residual stress in these regions has the most important influence on the performance of brazed synthetic diamond tools.

Table 1: Chemical composition of Ni-Cr brazing filler metals.

ELEMENT	Cr	C	B	Si	Fe	Ni
Mass fraction	16~18	0.6~0.8	2.5~3.0	4.0~5.0	5	balance

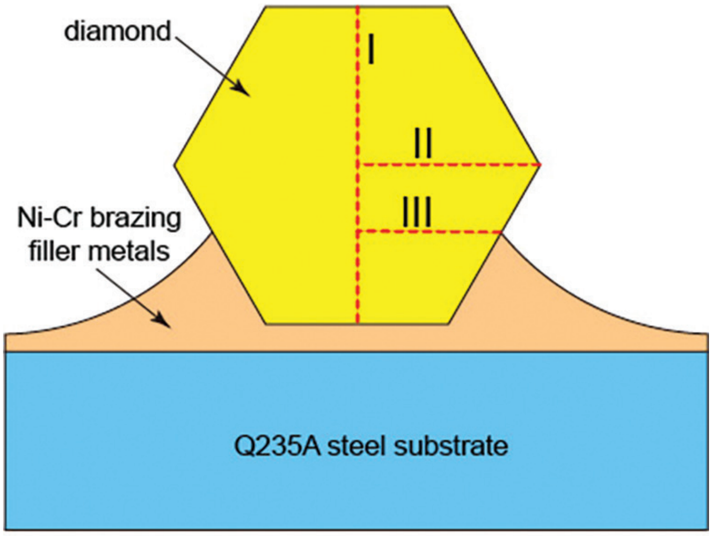

Figure 1: Schematic showing of brazed diamond grains specimen.

3. RESULTS AND DISCUSSION

3.1. Stress distribution in the central axis of brazed synthetic diamond grains

Previous research has discovered that the wave-number of 1332 cm^{-1} is the characteristic peak position without stress for synthetic diamond grain, the residual stress σ in synthetic diamond grain can be calculated by Equation 1 [10].

$$\sigma = -k \cdot \Delta\omega \quad (1)$$

Where, $\Delta\omega$ is the shift in the wave-number of the diamond's Raman spectroscopy-stokes-peak, k is constant 0.348 GPa/cm^{-1}. According to equation 1, the residual stresses in the central axis (the line I in Figure 1) of brazed synthetic diamond grains were achieved with different embedding depth, which is shown in Figure 2. In the brazed synthetic diamond grains, tensile stress coexists with compression stress, and the main is compression stress. Even if the embedding depth of brazed synthetic diamond grains is different, the residual stress has the same changing trends. From the top region to the bottom region of brazed synthetic diamond grains, tensile stress is translated into compression stress, and residual stress has a different rate of change for different embedding depth.

Before the embedding depth is less than 40%, the distribution of residual stresses is stable, there is not remarkable gradient. In the top region of brazed synthetic diamond grains, there is a steady region with width of 70 μm, the embedding depth has a small impact on the tensile stress magnitude, and the maximum value is below 80 MPa. Meanwhile, the fluctuation of residual stress is very small in the bottom region of brazed synthetic diamond grains; the maximum compression stress is below 100 MPa. The value and distribution gradient of residual stress is severely affected by embedding depth, when the embedding depth of diamond is greater than 40%. The compression stress is 100 MPa and 450 MPa for the embedding depth of 40% and 70%, respectively. The maximum compression stress reaches 502 MPa when the embedding depth is 80%. This indicates that the distribution gradient of residuals stress is quite distinct, and the residual stress becomes more and more large with the increase of embedding depth.

In the top region of brazed synthetic diamond grains, there is not brazing filler metals, brazed synthetic diamond grains is not being affected by brazing filler metals, or the affect is very small, at the same time, the cooling rate was controlled as 10 °C/min, which is very small and could form uniform temperature fields in brazed synthetic diamond grains, so the residual stress developing in the brazing progress is small. There is stress stability zone, when the embedding depth is below 40%. In the bottom region of brazed synthetic diamond grains, due to the large difference of thermal expansion coefficients and modulus of elastic between synthetic diamond grains and Ni-Cr brazing filler metals, the contraction capacity of Ni-Cr brazing filler metals is larger than synthetic diamond grains, the brazed synthetic diamond grains are in compression stressed condition. The greater of the embedding depth, the greater of compression stressed forms in brazed synthetic diamond grains.

3.2. Stress distribution in the central plane of brazed synthetic diamond grains

The residual stresses distribution in the radial direction of the central plane (the line II in Figure 1) of brazed synthetic diamond grains is shown in Figure 3. In the core zone of brazed synthetic diamond grains, the stress on diamond grains is compressive stress, the changes of stress value and stress gradient are small. The maximum stress and the minimum stress are 20 Mp and 70 Mp, respectively. However, in the margin region with the width of about 20 μm, the change of stress value and stress gradient are very obviously. Before the embedding depth is less than 50%, the stress on diamond grains is compressive stress, however, when the embedding depth is larger than 50%, the stress on diamond grains is tensive stress. When the embedding depth is 80%, the maximum stress is up to 270 Mp.

3.3. Stress distribution in the section planes of brazed synthetic diamond grains

Figure 4 shows the distribution of residual stress in the radial direction of the section plane (the Line III in Figure 1) between the brazed synthetic diamond grains and the top of Ni-Cr brazing filler metal. In the core

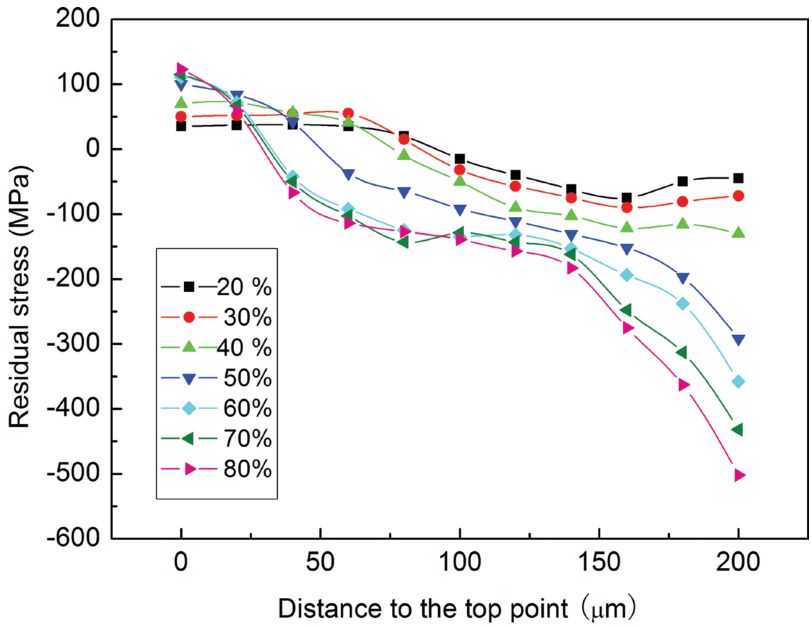

Figure 2: Residual stress distribution in central axis of brazed diamond grains.

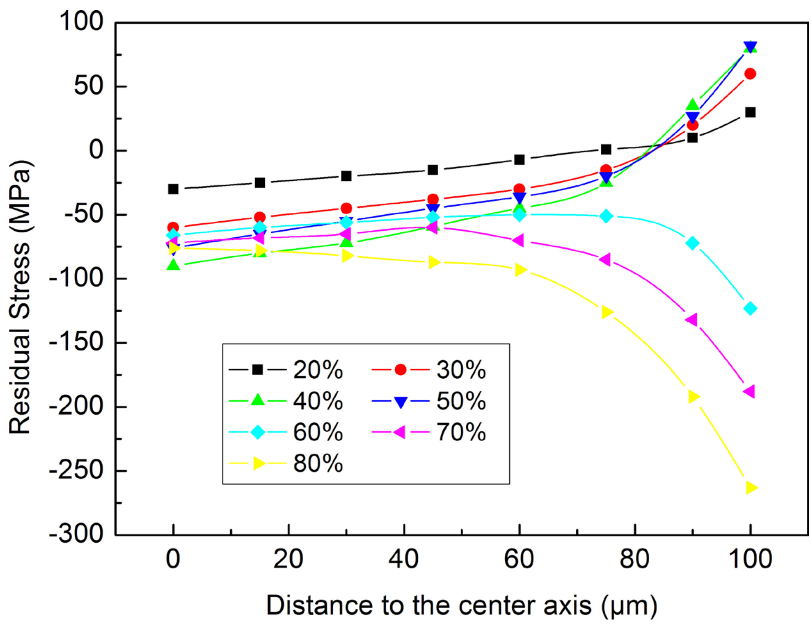

Figure 3: Distribution of residual stress in the center plane of brazed synthetic diamond grains.

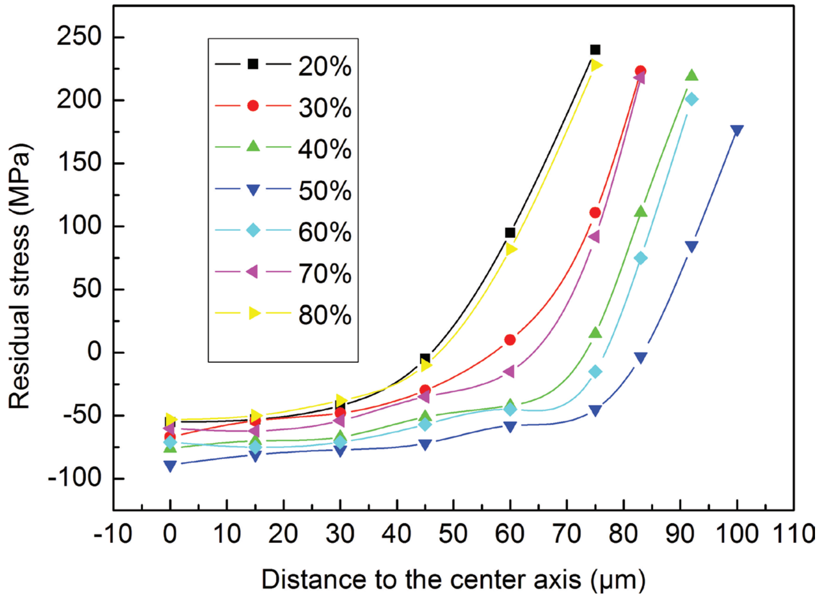

Figure 4: Distribution of residual stress in the section plane of brazed diamond grains.

region of the section planes, the influence of embedding depth on the residual stress is not evident. However, in the margin region of the section planes, the influence of embedding depth on residual stress if very evident and the distribution of residual stress also changes remarkably. For example, the tensile stresses are about 175 MPa and 220 MPa for the embedding depth of 50% and 70%, respectively, however, the compressive stress of 70 MPa in the core zone changes rapidly to the tensile stress of 210 MPa in the margin zone when the embedding depth is 40%. In addition, the distribution gradient of the residual stress is more obvious and the tensile stress becomes greater when the brazed synthetic diamond grains are embedded shallowly. As shown in Figure 4, the tensile stress reaches 240 MPa when the embedding depth is 20%.

3.4. Development Mechanism of residual stress in the brazed synthetic diamond grains

When synthetic diamond grains are brazed with brazing filler metals containing Cr, it forms bilayer interfacial chromium carbides Cr_3C_2 and Cr_7C_3, the Cr_3C_2 layer adjunct to the surface of brazed synthetic diamond grains, the Cr_7C_3 carbides layer on the top of Cr_3C_2, the microstructure has been systematically characterized by LU *et al.* [19] and CHEN *et al.* [20]. By the analysis results, in the margin region of the section planes between the brazed synthetic diamond grains and the surface of Ni-Cr brazing filler metal, the brazed synthetic diamond grains always endure the tensile stresses. The reason is that the margin region of the section planes is a special interface, where the mechanical properties change drastically between brittle synthetic diamond grains and ductile Ni-Cr brazing filler metal. In addition, the brazing products, Cr_3C_2 and Cr_7C_3 (as shown in Figure 5), have a relaxation effect on the residual stress between the synthetic diamond grains and the brazing filler metal depending on the transitional interface microstructure of diamond/Cr_3C_2/Cr_7C_3/ Ni-Cr brazing filler metal [21]. The average thermal expansion coefficients of synthetic diamond, Cr_3C_2, and Ni-Cr brazing filler metal over the temperature range of 20~1000 °C are about $1.1 \times 10^{-6}K^{-1}$,$10 \times 10^{-6}K^{-1}$, and $12.1 \times 10^{-6}K^{-1}$, respectively. The difference between the thermal expansion coefficients of brazing products can reduce the residual stress to a certain extent, but the compounds forming in brazing process could not yet completely eliminate the residual stresses caused by the great difference in the mechanical property of the synthetic diamond grains-Ni-Cr brazing filler metals joints.

In the inner zone of the section planes, the residual stress is always low. The reason is that the mechanical properties are quite similar except for the existence of the crystal defects of the synthetic diamond grains. In this cause, the trend is too weak to form the residual stresses on account of the varied thermal expansion coefficients. The residual stresses are mainly controlled by the faint distortion of the crystal lattice in the inner zone of the brazed diamond grains, which is induced by the crystal distortion.

In addition, synthetic diamond grain is a type of brittle material having high compressive strength and low tensile strength, the mechanical strength of the brazed synthetic diamond grains is seriously affected by tensile stress. In the margin region of brazed synthetic diamond grains, if the tensile stress is too high, the margin

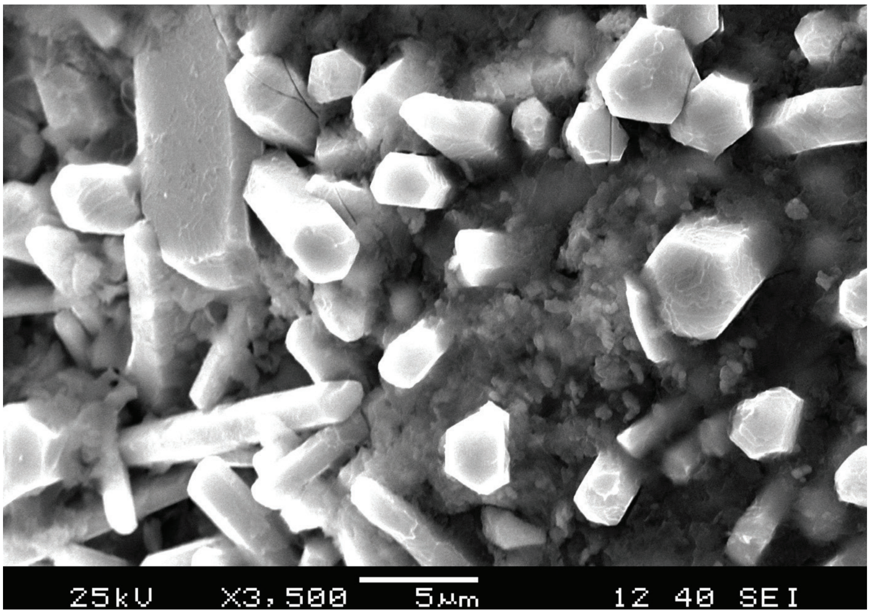

Figure 5: Carbide morphology on the surface of brazed diamond.

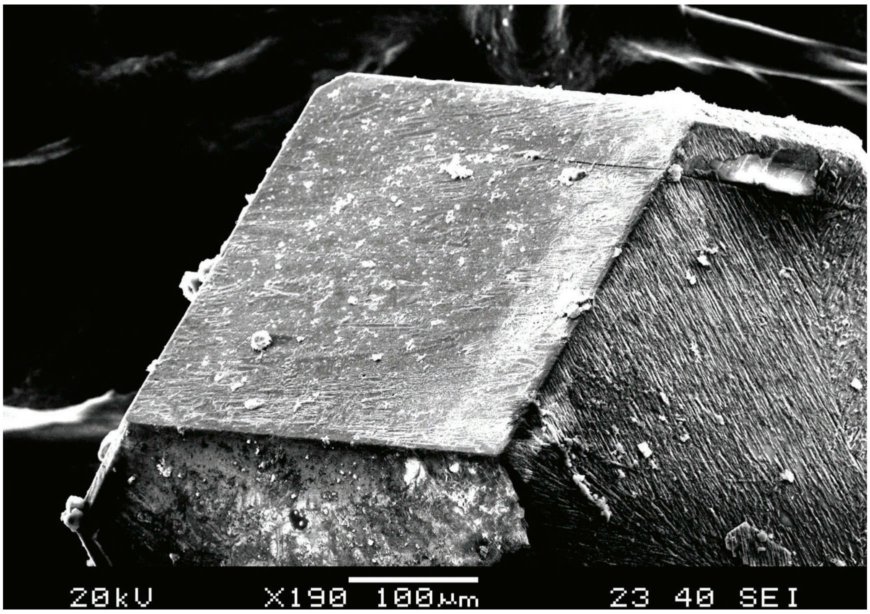

Figure 6: Crack in the brazed diamond grains with embedding depth of 20%.

region is a very dangerous area, where the synthetic diamond grains is likely to crack not only during the heavy-load grinding process, but also in the brazing process for the strength degeneration of the brazed synthetic diamond grains. So, the service life and the machining performance of the brazed synthetic diamond tools are decreased. When the embedding depth is 20%, it provides the apparent evidence that a crack has been formed and expanded in the brazed synthetic diamond grains, which is shown in Figure 6. It corresponds to the strength degeneration of the brazed synthetic diamond grains due to the maximum tensile stress of 240 MPa.

3.5. Embedding depth optimization of the synthetic diamond grains in brazed diamond tools

According to the above analysis, it can get the conclusion that the tensile stress is an important limiting factor to determine the mechanical strength of the brazed synthetic diamond grains. The maximum tensile stress has strong correlation with the embedding depth of the synthetic diamond grains in the Ni-Cr brazing filler metal layer. As a result, it is reliable to optimize the embedding depth of brazed synthetic diamond grains in brazed synthetic diamond tools according to the maximum tensile stress in the following selected regions: the central axis, the radial direction in the central plane, and the radial direction in the section planes between the brazed synthetic diamond grains and the surface of Ni-Cr brazing filler metal.

Based on Figure 2 to Figure 4, the influence of the embedding depth on the maximum stress along the central axis, the radial direction in the central plane, and the radial direction in the section planes between brazed synthetic diamond grains and the surface of Ni-Cr brazing filler metal, is illustrated in Figure 7. Results show that there is not liner relationship between the maximum tensile stress in brazed synthetic diamond grains and the embedding depth of the brazed synthetic diamond grains. The maximum tensile stress decreases with the increase of embedding depth when the embedding depth is below 50%, but the maximum tensile stress increases when the embedding depth is surpassing 50%. However, the change of the maximum tensile stress is not

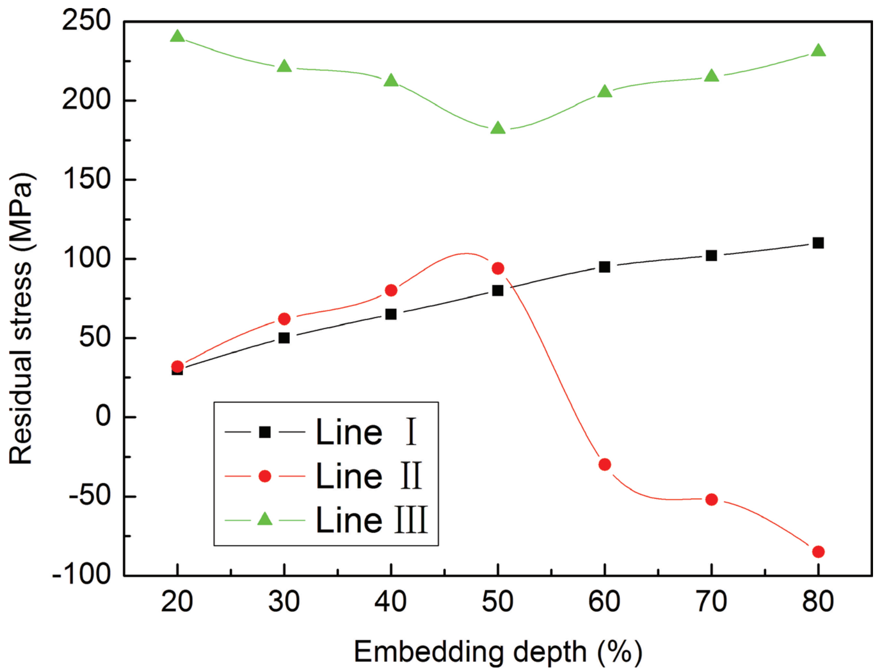

Figure 7: Maximum residual stress in the special region of brazed diamond grains.

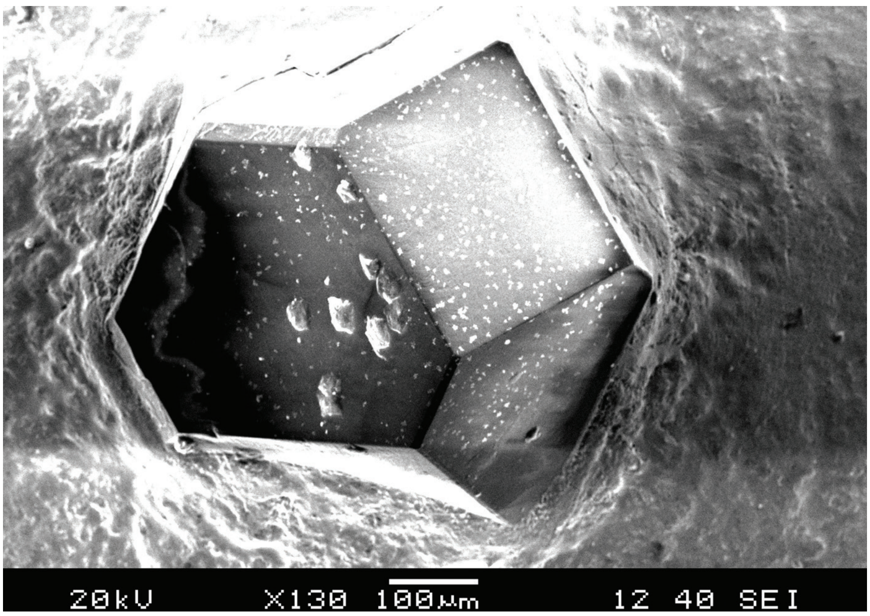

Figure 8: The brazed diamond grains with embedding depth of 50%.

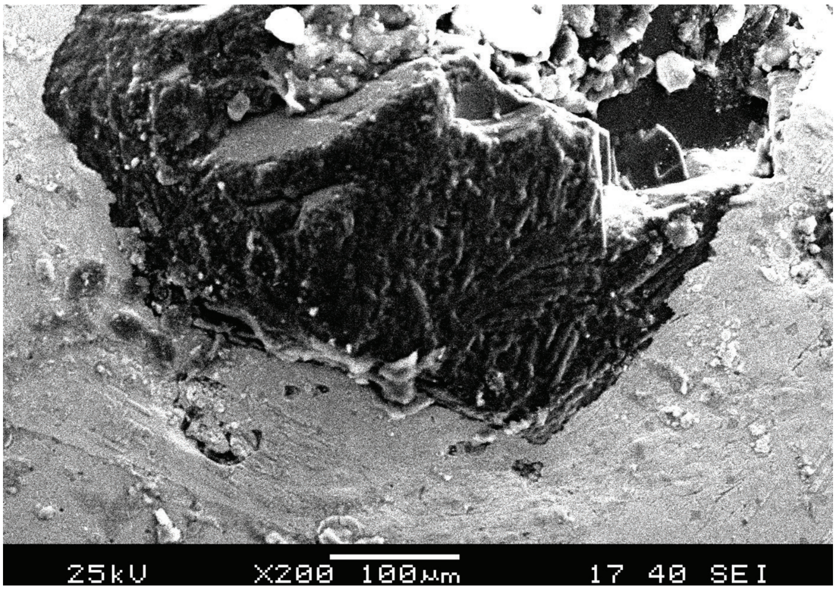

Figure 9: Abrasive wear of brazed diamond grains.

remarkably. It is attributed to the residual stresses are released via the ductile deformation of Ni-Cr brazing filler metal. Apparently, the maximum tensile stress is relatively small; it is not more than 200 MPa, when the embedding depth is about 40–60%. Consequently, synthetically considering the chip storage space on the working surface of the brazed synthetic diamond tools and the shearing resistance suffered during the grinding process for the difficult to machining material, the embedding depth is optimized at 40–50% of the whole synthetic diamond grains, which has been verified by grinding experiment. The mono-layer brazed synthetic diamond tools have longer service life, when the embedding depth is 40–50%. It is noted that the suitable embedding depth of synthetic diamond grains in brazed synthetic diamond tools should be synthetically considering according to the requirements of the machining process, it is not only the maximum tensile stress. During the grinding process, the applied synthetic diamond grains embedding depth of the abrasive tools may be further adjusted according to the requirements of the machining process. Not only to ensure the synthetic diamond grains having sufficient strength, but also to obtain essential chip storage space for brazed synthetic diamond tools.

In this work, the grinding experiments with embedding depth 50% was carried out for concrete (Figure 8). Figure 9 shows the abrasion wear for the brazed synthetic diamond tools. Cracking seldom takes place on the surface of synthetic diamond grains. Compared with the traditional electroplated diamond tools and the sintered diamond tools, the brazed synthetic diamond abrasive tools with optimum grains embedding depth show better grinding performance and longer service life.

4. CONCLUSIONS

In the core zones of the brazed synthetic diamond grains, the residual stress is stable without remarkable gradient. However, in the zones of the central axis, the margin region of both the central plane and the section plane between the brazed synthetic diamond grains and the surface of Ni-Cr brazing filler metal, the variation of the residual stress distribution is quite apparent.

The maximum tensile stress always exists in the margin region of the section planes between the brazed synthetic diamond grains and the surface of Ni-Cr brazing filler metal for the tremendous differences in the thermal expansion coefficients and modulus of elastic of brittle synthetic diamond grains and ductile Ni-Cr brazing filler metal.

The embedding depth of synthetic diamond grains in brazed synthetic diamond tools is optimized at 40–50% according to the maximum tensile stress in the brazed synthetic diamond grains to ensure the brazed synthetic diamond grains strength and the essential chip storage space of tools.

5. ACKNOWLEDGMENTS

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