Rare Metal Materials and Engineering
Volume 45, Issue 5, May 2016
Online English edition of the Chinese language journal

Cite this article as: Rare Metal Materials and Engineering, 2016, 45(5): 1152-1156.

ARTICLE

Interface Microstructure and Formation Mechanism of Diamond Abrasives Laser Brazed with Ni-Cr Solder

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Abstract: The laser brazing of diamond abrasives was investigated using Ni-based solder in an Ar atmosphere. The microstructure and the phase composition of the interface between diamond abrasives and Ni-based solder were analyzed using scanning electronic microscopy (SEM), energy dispersive spectroscopy (EDS) and X-ray diffraction (XRD). Meanwhile, the formation mechanism of carbides at the interface between solder and diamond abrasives was discussed. The results indicate that during laser brazing, the Cr-enriched layer around the diamond surface reacts with C in the diamond surface and consequently Cr_3C_2 is formed. Based on reaction thermodynamic and kinetic analysis, it is revealed that the interface reaction products can be formed via replacement reaction, which realize the tight combination between diamond abrasives and solder.

Key words: laser brazing; Ni-based alloy; interface microstructure; reaction mechanism

Diamond is a special kind of elemental carbon, particularly as its crystal structure belongs to the equiaxial face-centered cubic system. Its unique crystal structure gives it the greatest hardness and stiffness of all natural materials, as well as contributes to its perfect abrasion resistance, corrosion resistance, and chemical stability. Moreover, because of its outstanding mechanical features, diamond is an ideal raw material for machining tools that are used in the processing of hard and brittle materials. Thus, it has been widely applied in drills, saws and grinding tools, cutting, and polishing tools[1-3].

However, for traditional diamond abrasive consolidated grinding wheels, their abrasive particles are only mechanically embedded or inserted into clad layers or body metals. Due to the lack of binding force, these abrasive particles or clad layers are very prone to falling off during high efficiency grinding processes with relatively high loads. In order to increase the binding force, the thickness of binding agents has to be improved. This, however, results in problems such as a decrease of abrasive particle net height and chip space as well as the frequent blocking of abrasive wheels[2-4]. Currently, researchers all over the world are, therefore, focusing on developing a new generation of single-layer soldering diamond grinding wheels. By taking advantages of the high-temperature chemical and metallurgical reactions among abrasive particles, active solders and wheel bodies, the tight combination between binding agents and abrasive particles is expected to be realized. Thus, the requirements of heavy load and high efficiency grinding process can be satisfied.

Experts investigated the laser brazing of diamond thin-wall drills. They studied the process and the interface combination of diamond particles laser welding using Cu-based solders. Moreover, the soldering interface bonding characteristics were analyzed between diamond particles and the Cu-based alloy as well as the Ni-based alloy. These experts have described the segregation phenomena of active elements at the bonding interface in addition to determine the species of a part of these new compounds. However, no further reports concerning the interface microstructure and formation mechanism have been published[3-6]. In the present paper, scanning electron microscopy (SEM), energy disperse spectroscopy (EDS) and X-ray diffraction (XRD) were adopted to investigate the morphology and the microstructure of new compounds which are generated on the brazed abrasive particle surface under the condition of laser scanning heating. In addition, the formation

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Received date: April 14, 2015
Foundation item: National Natural Science Foundation of China (U1204517)

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mechanism of interface microstructures was discussed via the aspect of interface reaction thermodynamics and the dynamic diffusion behavior of related atoms. Thus, instructions are provided for follow-up studies that are designed to further improve the grinding performances of diamond grinding wheels by adjusting the microstructure of bonding interfaces.

1 Experiment

The material used in the following experiments was uncoated diamond with grain sizes of 287~396 μm. The base material was 45 steel, which was manufactured into cuboid specimens of 25 mm×15 mm×10 mm dimension. The solder used was Ni-Cr alloy with a melting temperature range of 1000~1050 ℃. In order to eliminate the influence of various impurities as well as to guarantee the spreading and wetting effect of fusion solder on the soldering base material surface, degassing and decontamination treatments were carried out on the base material and abrasive particles. Furthermore, specimens were prepared according to the sequence of the base material/solder/abrasive particles, and then placed into the soldering device for laser brazing. The soldering device consisted of a CO_2 laser, an NC machining tool and a gas protection apparatus.

The laser brazing experiment was conducted in a TJ-HL-T5000 crossflow CO_2 numerical controlled laser, with the lasing mode initially set to TEM00. During the experiment, the laser power, scanning frequency, and spot size were adjusted to control the brazing procedure[7,8]. Based on technological tests, an optimized combination of the spot size, laser power, and scanning frequency was determined so as to accomplish the brazing of diamond abrasive particles. Laser brazing is a fast but unbalanced heat-circulation process, as shown in Fig.1.

The overall, side face and eroded morphologies of the brazed diamond specimens were characterized using SEM (JSM-6300, JEOL). The cross-section elemental distribution was analyzed using EDS (KEVEX) in the linear scanning mode. Structure analysis of the carbides on the diamond surface was also conducted with XRD (D'max, Rigaku).

2 Results and Discussion

2.1 Interface element distribution of brazed diamond

Fig.2 demonstrates the bonding morphology of the Ni-Cr alloy and diamond after soldering. It can be seen from the appearance that the diamond edge is cladded by a large amount of selenodont-like Ni-Cr alloy. Thus, it is clearly demonstrated that the Ni-Cr alloy has favorable wettability with diamond particles, indicating that wetting reactions occurs between the diamond abrasive particles and the fusion solder. In addition, the diamond particles have complete crystal shapes, definite edges and corners without any cracks or graphitization.

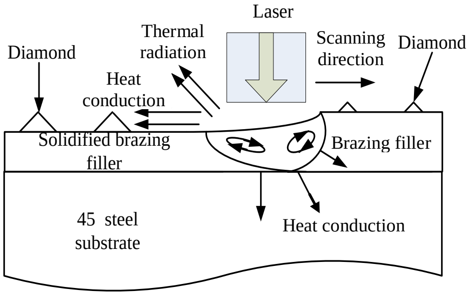

Fig.1 Sketch of laser brazing

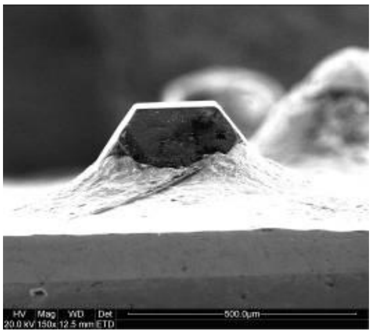

Fig.2 SEM image of the diamond side face

Fig.3 demonstrates the bonding features of the interface between diamond particles and the Ni-Cr alloy. As shown in the figure, Ni, Cr, and Si all have obvious concentration gradients. Clearly, the Cr concentration near the diamond is considerably higher than that far away from the diamond, thus indicating that the Cr atoms diffuse and aggregate during soldering. Even though the interface element distribution curve in Fig.3 has

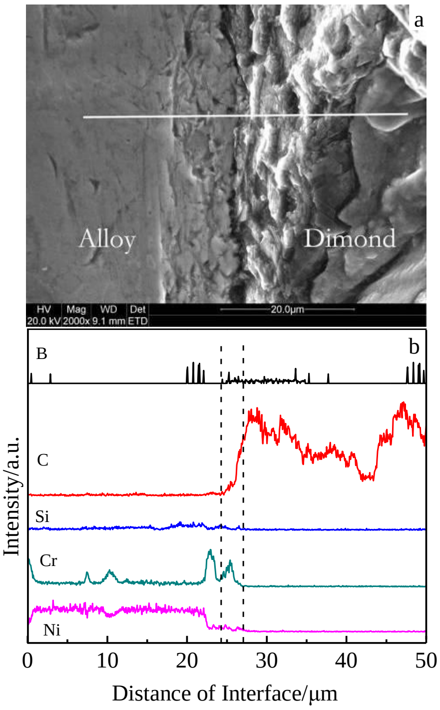

Fig.3 Bonding interface between a diamond abrasive particle and the Ni-Cr solder (a) as well as the elemental distribution across the interface (b)

proven the atomic diffusion across the bonding interface between the diamond abrasive particles and the solder, the species of the newly generated compounds are still unknown.

However, the distribution patterns of these compounds greatly influence the structure transition between the abrasive particles and the solder layers because the Ni-based solder and diamond abrasive particles have different properties. More specifically, the solder layer is a kind of plastic material that is bonded by metallic bonds, whereas the abrasive particles belong to brittle material which is bonded by covalent bonds. If the composition and the structure between the abrasive particles and solder layer can transit layer-by-layer via taking advantage of the bonds inside the compound, it will play a significant role in promoting the reduction of residual stress inside the soldered joints between dissimilar materials in addition to improving their bonding strength[5,7,8].

2.2 Microstructure of the interface between the diamond abrasive particles and Ni-based solder alloy

In order to conduct an in-depth analysis on the species and the microstructures of the newly generated compounds on the surface of brazed diamond, soldered specimens after cutting were selectively eroded to get the morphology and XRD pattern, as shown in Figs.4, 5, and 6.

It is obvious that there are reaction products growing along the shearing direction on the brazed diamond surface; the XRD pattern of brazed diamond indicates that these products are Cr_3C_2. In the interface reaction system consisting of the diamond and Ni-Cr solder, the Cr concentration in the solder alloy is the highest, with relatively high reaction activity. A previous study revealed that the Cr-C reaction was a kind of diffusion reaction[5]. According to thermodynamics[9], the standard free energy ΔG_0 of Cr and C forming Cr_3C_2 at 1050 ℃ is –10897 J/mol. With this very low ΔG_0, Cr easily reacts with C to form carbide compounds. As for the diamond-metal system, due to the C concentration gradient caused by diffusion, Cr_3C_2 nucleates on the diamond surface and grows outward, as is revealed by the experimental results. If a certain reaction time is allowed, a resulting layer of carbides is formed on the diamond surface. In addition, the linear expansion coefficient of Cr_3C_2 (9.70×10^{-6} ℃$^{-1}$) is between that of the diamond (about $(1.5\sim4.8)\times10^{-6}$ ℃$^{-1}$) and that of the solder (about 1.2×10^{-5} ℃$^{-1}$), and it is able to relieve the possible stress effect produced by the difference between the linear expansion coefficients of the diamond and solder alloy. Thus, this Cr_3C_2 layer has a strong binding force to the diamond as well as excellent thermal conductivity.

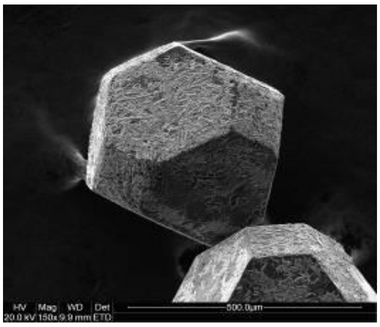

Fig.4 Surface morphology of eroded diamond

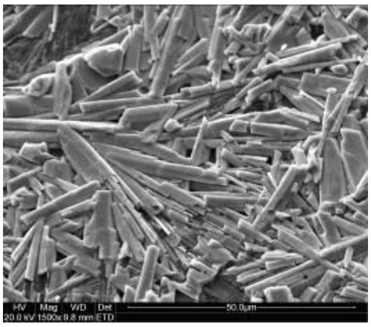

Fig.5 Morphology of products on the diamond surface

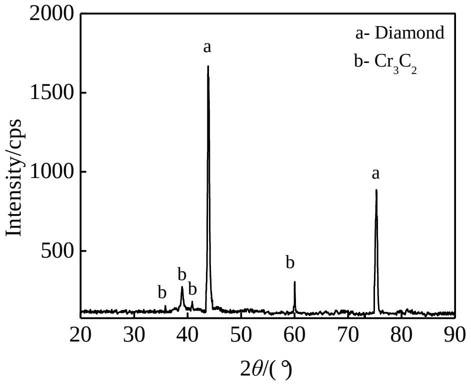

Fig.6 XRD pattern of laser brazed diamond

2.3 Dynamic analysis on the interface reaction between diamond and Ni-Cr solder

The soldering interface reaction between diamond and Ni-Cr alloy is a reaction diffusion process that is primarily caused by the diamond C atoms diffusing into the solder layer, and the solder Cr atoms aggregating towards the abrasive particle surface. The occurrence of the interface reaction diffusion layer is believed to be caused by the following two aspects: the physical penetration that results from the capillarity of liquid solder, the diffusion of Cr in the solder alloy and its chemical reaction with diamond particles. Hence, this diffusion phenomenon is also named as reaction diffusion. The rate of the reaction diffusion is comprehensively determined by the chemical reaction rate and the diffusion rate of Cr atoms.

During the laser brazing of the diamond abrasive particles, when the solder specimen is heated to a certain temperature by laser scanning, the vibration of the diamond lattice becomes fierce. Thus, the C atoms or C atom groups begin to diffuse into the solder through defects, such as pore vacancies and vacancy groups. Since there are dangling bonds on the C atom surface, while Cr is a kind of transition metal with an electron deficiency in the 3d shell layer, they form carbides at elevated temperatures via the interactions between d-sp^2 and d-sp^3. According to the Cr-C phase diagram, the formation of its reaction layer has to follow the relationship between concentration and each phase region presented in the diagram, i.e. phases with higher concentration are formed after those with lower concentrations, and these phases develop along the direction that points to the maximum thermodynamic stability. Therefore, the interface consists of δ, α and β carbides in turn from the diamond to solder. Since the surface chemical energy is higher than that inside, the diffusion activation energy of surface atoms is lower than those inside. At the same time, there are many crystal defects in the diamond surface, which are distributed unevenly. The chemical energy of atoms at the lattice distortion sites in diamond is the highest, while the atoms in the crystal surface arrange anomaly. The diffusion activation energy of atoms is lower here, and thus, the atoms diffuse faster. Hence, δ carbide dots (Cr_3C_2) first aggregate at the defects on the diamond surface, such as the dislocation outcrop sites and growth steps. As time continues, these dots grow into chips, as shown in Fig.5. The whole process consists of diffusion and phase transition[10].

When Cr_3C_2 crystals begin to nucleate and grow with diamond as their grain boundaries, many active Cr atoms are consumed at the interface area. Thus, the Cr concentration at the interface decreases, which leads to a serious increase of the Cr concentration gradient inside the solder layer, and provides the driving force for the Cr atoms far away from the abrasive particles inside the binding agent layer to continuously diffuse towards the interface micro area. The higher the Cr concentration in the solder, the larger the concentration gradient will be. In return, the diffusion rate of Cr is higher, which is beneficial to the thickening of the interface reaction layer. Fig. 7 is a schematic of the interface reaction, in which C_0 stands for the initial Cr content in the solder layer. $C_{Cr}^{Diamond}$ is the Cr concentration in the diamond, C_{Cr}^{Comp} is the Cr concentration in the interface compound, and C_{Cr} is the Cr concentration of the solder layer near the interface, as well as their change with time.

As temperature increases, the solder becomes liquid, Cr and C continue diffusing with the on-going reaction. The diffusion of Cr is mainly controlled by the concentration gradient at the interface between the solder and abrasive particles. The process of mutual reaction between Cr and C can be considered as the movement of phase interfaces controlled by Cr diffusion; therefore the variation of Cr and C concentrations leads to multi-phase formation during diffusion. Moreover, as indicated in the Cr-C phase diagram, the formation of the reaction layer has to follow the relationship between the concentration and each phase area. That is, on the diamond surface, carbides form sequentially as $Cr_3C_2 \rightarrow Cr_7C_3 \rightarrow Cr_{23}C_6$.

Furthermore, the structure of carbides is decided by the relative amount of active C atoms and Cr atoms. When Cr is insufficient, Cr_3C_2 occurs, whereas Cr_7C_3 is produced when the Cr is sufficient. The excess Cr atoms will form $Cr_{23}C_6$ [8,10,11]. In the present study, only Cr_3C_2 is detected. The reason may be that since the action duration of laser brazing is very short, and the driving force is not strong enough, the Cr atoms are unable to diffuse to reach the concentration required for the occurrence of Cr_7C_3 and $Cr_{23}C_6$.

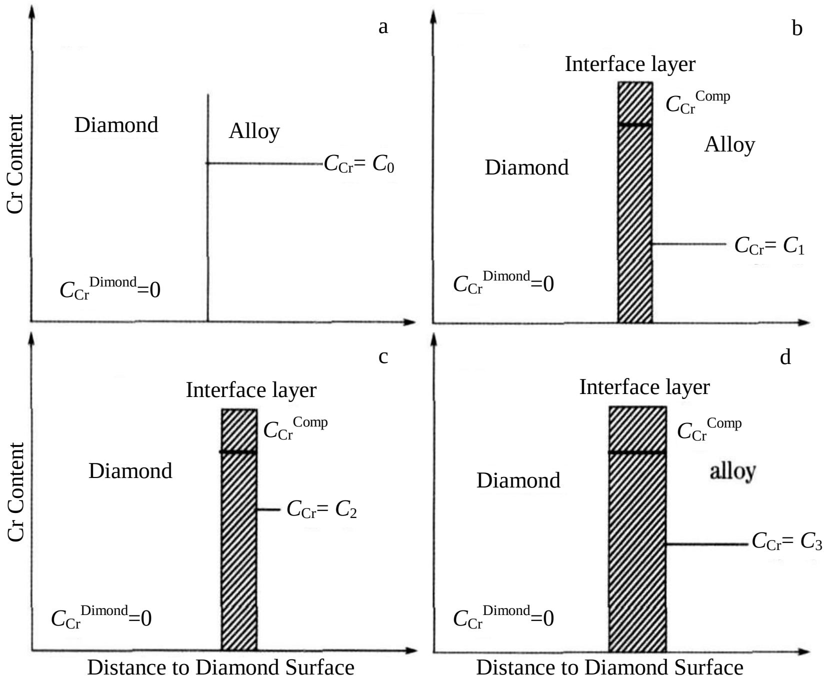

Fig.7 Schematic of the interface reaction: (a) initial state, (b) $t=t_1$, (c) $t=t_2$, and (d) final state

3 Conclusions

1) The active element Cr in Ni-Cr alloys and the C in the abrasive particles will diffuse and segregate during the laser brazing process.

2) The microstructure corresponding to Cr_3C_2 occurs at the interface area. This kind of microstructure has favorable chemical bonds and mechanical performance transition characteristics which makes the linkage between the diamond and the solder.

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Ni-Cr 合金钎料激光钎焊金刚石磨粒界面显微结构及形成机理

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摘　要：采用 Ni-Cr 合金钎料，在 Ar 气保护条件下，对金刚石磨粒进行了激光钎焊研究。采用扫描电镜(SEM)和能谱仪(EDS)及 X 射线衍射仪(XRD)分析金刚石磨粒与 Ni-Cr 钎料结合界面的组织结构与物相组成，并研究了钎料与金刚石界面处碳化物的形成机理。结果表明，激光钎焊过程中，在金刚石表面形成的富 Cr 层与金刚石表面的 C 元素反应生成碳化物 Cr_3C_2。通过反应热力学与动力学分析显示，界面反应产物可以依靠置换反应形成，使金刚石磨粒与钎料实现了牢固结合。

关键词：激光钎焊；Ni-Cr 合金；界面微结构；反应机理

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