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The Development of Manufacturing Technology of CVD Diamond Thick Film Tools

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Abstract. The key manufacturing technology of CVD diamond thick film tools is introduced, including thick film preparation, cutting, welding and edge polishing. The problems existing in manufacturing of CVD diamond thick film tools are analysed. The development trends of manufacturing technology of CVD diamond thick film tools are discussed.

1. Introduction

In recent years, with the rapid development of automobile, aerospace, precision instruments and other manufacturing fields, a large number of difficult-to-machine materials which are light-weight and high-strength are widely used. High efficiency, high precision and high quality cutting requirements of difficult-to-machine materials cannot be satisfied by common high speed steel and carbide tools. Diamond tools have gradually become the mainstream tool for cutting difficult-to-machine materials due to the high hardness, good wear resistance, high thermal conductivity, low friction coefficient and stable chemical properties, etc. Chemical vapour deposition (CVD) diamond thick film tool is one of the types of diamond tools. It not only makes up for the shortcomings of natural diamond tools such as crystal orientation selection when grinding and high price, but also overcomes the defects of poor life of polycrystalline diamond (PCD) tools and low interface bonding strength of CVD diamond thin film coated tools. After years of basic research and application, CVD diamond thick film tools have entered a practical stage, and some companies in the United States, Japan and some European countries already have products on the market. In China, some universities, research institutes and tool manufacturers have done a lot of research on them and achieved some results. However, the performance index of high quality and high precision is still not reached due to the constraints of manufacturing technology such as diamond thick film preparation, cutting, welding and edge polishing, which leads to the relatively small scale of practical application of diamond thick film tools. Therefore, under the background of “Made in China 2025”, it is of great significance to improve the manufacturing technology of diamond thick film tools in China for obtaining low cost and high quality diamond tools, meeting the cutting requirements of difficult-to-machine materials, getting rid of restriction of imported tools and improving China’s position in the international tool market.

2. Manufacturing technology of CVD diamond thick film tools

CVD diamond thick film tools are made by cutting the diamond thick film ($\delta > 0.5\text{mm}$) prepared by chemical vapour deposition, then welding it on the tool matrix and grinding and polishing it finally. As shown in Figure 1, the tool structure is composed of diamond thick film, matrix, tool head and tool body.



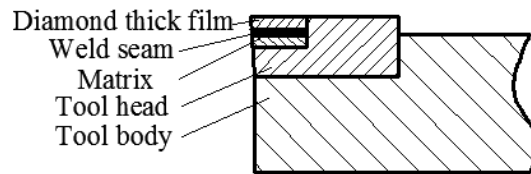


Figure 1. Structure chart of CVD diamond thick film tool.

2.1. Preparation technology of CVD diamond thick film

Under high temperature and low pressure conditions, CVD diamond thick film is prepared by releasing energy through the CVD device to activate the mixture of carbon and hydrogen, forming active diamond carbon atoms, and depositing and growing interactively on the matrix. The prepared diamond thick film is required to have high purity, uniform and tight bond grain, large film-forming area, small internal stress and few micro-cracks. At present, the main methods of preparing diamond thick film in industry include hot filament chemical vapour deposition (HFCVD), microwave plasma chemical vapour deposition (MPCVD), direct-current arc plasma jet chemical vapour deposition (DC Arc Plasma Jet CVD) and direct current plasma assisted chemical vapour deposition (DC-PACVD). Technical characteristics of different deposition methods of diamond thick film are shown in Table 1. It can be seen from Table 1 that each method has its own advantages and drawbacks. In general, MPCVD is considered as the preferred method to prepare high quality diamond because of its high plasma density, no discharge electrode pollution and good control. However, it is only used in the fields of microelectronics, optics and so on which require high quality of diamond film due to the high cost of MPCVD equipment. HFCVD is widely used as raw materials of diamond thick film tools because of its simple equipment, low cost, easy control of production process and large area of thick film. Nevertheless, from the point of view of current preparation technology, the supply of CVD diamond film is far from meeting the demand of the social market. In the preparation of diamond thick film, the low deposition rate and the low quality lead to the low yield of diamond thick film, which is the main reason for the relatively small number of diamond thick film in the market. In order to solve these problems, researchers have done amount of work in optimizing deposition parameters [1,2], improving deposition equipment [3,4] and adding auxiliary gases [5]. In addition, in order to reduce the usage of hazardous gas, the investigator tried to use the liquid diffusion as a carbon source for synthetic diamond film [6,7]. However, there is still a certain gap to meet the deposition requirements of large-area, high-efficiency and high-quality of diamond thick film at the same time.

Table 1. Technical characteristics of different deposition methods of diamond thick film [8].

Methods	Deposition rate ($\mu\text{m/h}$)	Advantages	Drawbacks
HFCVD	1~10	Low-priced equipment and easy control; Large area at low pressure	Degradation of the filament; Poor quality of diamond thick film; Low growth rate
MPCVD	0.1~34	High diamond quality; Good stability; No electrode pollution	Small deposition area; Low growth rate; High production cost
DC arc plasma Jet CVD	5~930	High diamond quality; Highest linear growth rate;	Small deposition area; High production cost; Process control difficult
DC-PACVD	6~25	Large area at low pressure; Simple set-up; Low-priced equipment	Low growth rate at low pressure; Contamination through electrode

2.2. Cutting technology of CVD diamond thick film

CVD diamond thick film need to be cut into a certain shape according to the different shapes of diamond thick film tools. Conventional mechanical cutting methods are not suitable for diamond thick film because of its high hardness and wear resistance. At present, the main methods of cutting diamond thick film are wire electron discharge machining (WEDM), abrasive water jet (AWJ) cutting and laser cutting. CVD thick film is pure diamond and non-conductive, which hinders the application of more mature EDM technology. To cope with this problem, some researchers have conducted studies on improving the conductivity of diamond thick film. For example, in order to improve its machining abilities and finally manufacture it by EDM method, researchers added boron to diamond thick film [9,10]. However, the improved diamond thick film still has poor electrical conductivity, which requires further research before it can be truly applied to production practice. AWJ cutting method has the advantages of simple structure and easy operation, but its application and development are limited by the problems of low cutting efficiency, uneven incision and rough cutting surface. In contrast, laser cutting method has the characteristics of non-contact, small slit, high efficiency and complex cutting trajectory, etc. It is considered to be an ideal method for cutting CVD diamond thick film [11]. Laser can not only cut the diamond thick film into the required shape and size, but also cut the relief angle of the tool directly. In order to achieve the ideal cutting effect of high efficiency and high quality, scholars have done a lot of research. Tokarev et al. [12] established the theoretical analytical model of diamond thick film by laser cutting, and studied the effects of laser power, pulse and incident angle on cutting quality. Yan et al. [13] researched the influences of laser focal position, frequency, voltage and cutting rate on the cutting quality of CVD diamond thick film by using Nd:YAG laser machine. According to his result, he found that the slit was smaller when the focus was on the surface of diamond thick film, and the cutting effect was shown in Figure 2. As a result, he obtained narrow slits with high cutting surface quality by optimizing the laser focus position, choosing the appropriate cutting rate and repetition frequency. So far, researchers have improved the cutting efficiency and quality of diamond thick film by improving its conductivity, optimizing laser cutting parameters and improving laser cutting equipment [14]. However, the CVD diamond thick film still has some defects such as cracks, ablation and internal stress. Therefore, the cutting technology of diamond thick film still needs further research.

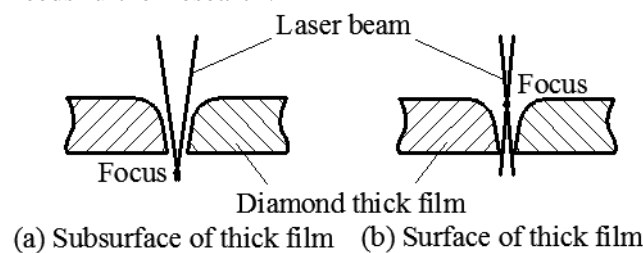


Figure 2. Diagram of cutting effect of laser focus on different positions of diamond thick film.

2.3. Welding technology of CVD diamond thick film

The high interfacial energy between diamond and common alloys prevents diamond from being infiltrated by common low melting point alloys. In addition, great internal stress exists between the diamond and the substrate owing to the great difference of thermal expansion coefficient, which causes cracks or fracture of diamond under thermal stress, so the weld-ability of diamond is very poor. In order to solve these defects, researchers proposed the method of brazing diamond. At present, two techniques are used to improve the wettability and reduce the thermal damage of diamond. One method is to improve wettability and affinity of diamond by adding some active elements to conventional filler metals. For example, Ti is added to Ag-Cu alloy filler metal. Li et al. [15] used Ag-Cu-Ti active filler metal as the solder material to effectively achieve the high-strength connection between diamond and matrix. Another method is to coat the diamond surface with metal and then braze it with high melting point filler metal. The reason is that surface metals protect diamond effectively, reduce the thermal damage and improve the wettability of filler metal on diamond surface.

Zou et al. [16] deposited Ti/Cu layer on diamond thick film by magnetron sputtering. Then the surface Cu and Ti layers were corroded by hot concentrated sulfuric acid, while TiC layer remained on the surface. After this, the coated diamond thick film was brazed with hard alloy. Result show that the weld strength of diamond thick film on hard ally is fit for machining. In addition, scholars have done a lot of research on the factors affecting the welding strength of diamond thick film and matrix from the point of view of welding technology [17-19]. Whether it is surface metallization or active solder welding, higher welding temperature affects the performance of CVD thick film tools to a certain extent. Therefore, scholars still need to further research how to control the welding temperature reasonably.

2.4. Polishing technology of CVD diamond thick film tools

In order to reduce the surface roughness of the tool and improve the surface quality of the tool, it is necessary to grind and polish the tool. However, it is very difficult to grind and polish CVD diamond thick film because of its high hardness and high wear resistance, which largely limits the application of CVD diamond thick film tools in precision and ultra-precision cutting. Therefore, polishing technology has become a key manufacturing technology in the application of CVD diamond thick film tools. At present, according to its polishing principle, the polishing technology of CVD diamond thick film tools can be divided into mechanical polishing, thermochemical polishing, chemical-assisted mechanical polishing, ion beam polishing and laser polishing, etc. The characteristics of various polishing methods are shown in Table 2. From the table, we can see that different polishing methods have their own advantages, disadvantages and scope of application. No polishing method can fully meet different application requirements. Therefore, different polishing methods should be selected according to the shape of CVD diamond thick film, the requirements of final surface quality, polishing efficiency and the limitations of polishing equipment.

Table 2. Characteristics of various polishing methods for CVD diamond thick film tools.

Methods	Polishing mechanism	Advantages	Drawbacks
Mechanical polishing	Micro cutting	Low cost; Light pollution	Low polishing efficiency; Affected by natural vibration and shock of equipment; Limited by polishing of plane shape
Thermochemical polishing	Graphitization; Carbon diffusion	Low cost; High polishing efficiency; High polishing quality; Small mechanical damage	High pollution; High processing temperature; Affected by natural vibration and shock of equipment; Limited by polishing of plane shape
Chemical assisted mechanical polishing	Oxidation	Low cost; High polishing efficiency; Light pollution	Affected by natural vibration and shock of equipment ;Limited by polishing of plane shape
Ion beam figuring	Sputtering; Etching	High polishing quality; Not limited by shape; Light pollution	Low polishing efficiency; High cost
Laser polishing	Evaporation; Etching; Graphitization	Light pollution; High polishing efficiency; Not limited by shape	High cost; Only suitable for rough processing

3. Development trends of manufacturing technology of CVD diamond thick film tools

3.1. *Improving chemical vapour deposition technology of diamond thick film*

There are many factors to be controlled in the preparation of CVD thick diamond film, such as carbon sources and hydrocarbon concentration, gas flow rate, diamond nucleation density, temperature and substrate material. Each factor will affect the deposition rate and quality of diamond thick film. So far, researchers have mainly optimized the whole process of thick film growth by changing hydrocarbon concentration or adding a single auxiliary gas (oxygen, carbon dioxide, nitrogen, argon). Few scholars discussed the influence of gas (type, concentration, flow rate) respectively from the nucleation stage and growth stage of thick film. Therefore, the future development direction is to accurately control the type, concentration, flow rate of gas source respectively from the nucleation stage and growth stage of thick film, and consider other factors comprehensively, so as to improve the nucleation density and uniformity in the nucleation stage and increase the growth rate and diamond thick film purity in the growth stage. Finally, the goal of producing high quality of diamond thick film with high efficiency will be achieved.

In addition, there are differences between the actual concentration of each gas controlled by mass flowmeter and the pre-set concentration, so it is impossible to control the gas concentration accurately. Tunable diode laser absorption spectroscopy (TDLAS) technology is based on the change of the output intensity of the light source absorbed by the gas to detect the gas concentration. It has the characteristics of high sensitivity, high precision, good stability and fast response. Therefore, TDLAS technology can be used to improve the intake system of deposition equipment in the future, so as to accurately control the concentration of gases in different stages in real-time online.

3.2. *Improving laser cutting technology of CVD diamond thick film*

The mechanism of laser cutting of diamond thick film is that the diamond is evaporated, gasified or graphitized at high temperature by laser, so as to remove the diamond material and achieve the cutting purpose finally. But this method will produce higher temperature in laser cutting. Heat-affected zones (HAZ) are formed at the cutting site inevitably, which leads to micro-cracks, ablation and faults in the diamond thick film, which also reduces the fracture strength and practical performance of the diamond thick film to a certain extent. Therefore, it is very important to control the HAZ in the process of laser cutting of diamond thick film. At present, the research on laser cutting of diamond thick film mostly focuses on the influence of process parameters on laser cutting quality, while the research on the heat-affected zone and its influence caused by laser cutting is relatively small. Therefore, it is necessary to study the microstructure and phase structure of HAZ from the mechanism of laser cutting of diamond thick film in the future, so as to minimize the probability of thick film cutting defects. In addition, it is also necessary to actively explore laser composite cutting technology. For example, laser micro jet (LMJ) is a composite technology of laser and water jet. It not only has the intrinsic thermal effect of laser processing, but also has the cooling and polishing effect of water jet processing, which can effectively solve the problem of excessive cutting temperature.

3.3. *Innovating polishing technology of CVD diamond thick film tools*

The polishing efficiency and quality of CVD diamond thick film cutting tools are closely related to the polishing process. Although there are many polishing methods, these single methods cannot meet the requirements of high efficiency, economy, high precision and high quality polishing. It has been proved that compound polishing achieves good polishing effect. The key lies in the reasonable combination of different polishing methods and the choice of different polishing methods in different polishing stages. Therefore, we should boldly try all kinds of composite polishing methods in the future work. In addition, we also need to boldly conceive, dare to innovate and provide new polishing ideas on the basis of various polishing methods, such as applying tiny vibration to the polishing disc to improve the polishing effect and using ultra-high speed method to raise the surface temperature of CVD diamond thick film to achieve thermochemical polishing.

Furthermore, it is necessary to strengthen the research of polishing auxiliary institutions and online monitoring system. Only by improving the performance of polishing auxiliary institutions and controlling polishing process parameters on line, can we realize the goal of digitalization and automation of tool polishing, and gradually get rid of the situation that polishing can only rely on manual technology.

3.4. Establishing quality evaluation index system of CVD diamond thick film tools

The manufacturing of CVD diamond thick film tools includes many stages, such as thick film preparation, cutting, welding and tool polishing. Each stage has its own quality requirements. Only by meeting the quality requirements of each stage at the same time can we produce high quality CVD diamond thick film tools. However, there is no quality evaluation index system of CVD diamond thick film tools at present. Therefore, the establishment of quality evaluation index system of diamond thick film tools can not only realize the quality control of cutting tools, but also have great significance for the development and application of cutting tools. The quality evaluation of CVD diamond thick film tools is a comprehensive process, which involves thick film quality, cutting quality, welding quality and polishing quality. The quality indexes of CVD diamond thick film tools are shown in Table 3.

Table 3. The quality indexes of CVD diamond thick film tools.

Manufacturing process	Quality index
Thick film preparation	Morphology of thick film(crystal orientation, grain size and surface roughness, etc.); Fracture strength of thick film; Purity of thick film; Internal stress of thick film; Defects of thick film (pore, slag inclusion and micro-crack, etc.)
Thick film laser cutting	Morphology of thick film cutting surface; Defects on cutting surface(micro-cracks, ablation and fault, etc.)
Thick film welding	Weld defects(ablation, pore, crack and unfilled weld, etc.); Welding strength; Weld residual stress
Tool edge polishing	Tool surface roughness($\leq 0.01\mu\text{m}$); Tool edge sharpness ($\leq 0.1\mu\text{m}$); Precision of tool edge profile($\leq 0.05\mu\text{m}$) [20]

4. Conclusions

The price of CVD diamond thick film tools is lower than that of natural diamond tools, and its cutting performance is higher than that of PCD tools. CVD diamond thick film tools can also be used in the field of precision or even ultra-precision machining. It has broad application prospects. At present, some breakthroughs have been made in the manufacturing technology of CVD diamond thick film tools, but there is still a long way to go before large-scale industrial application. With the improvement of all aspects of tool manufacturing technology, CVD diamond thick film tools will truly achieve the goal of high quality and low cost, and play an important role in the tool market.

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