The Design of Large-aperture HFCVD Diamond-coated Drawing Die Preparation System and Experimental Study on Its Application

Abstract. As a new type of die, HFCVD diamond-coated drawing die registers a great application prospects and market potential because of its performance advantages. This study mainly focuses on the preparation system of diamond coating for large-aperture drawing die.
According to the finite element analysis of the temperature field of the die base on HFCVD process, hot filament parameters on the temperature distribution of the die base is studied. And on the basis of the sdudy, a new HFCVD coating mold preparation system with rotating U-shape groove is designed, which can produce more uniform coating. The deposition experiments were carried out on the inner wall of the drawing die by the HFCVD coating mold preparation system. The cross-sectional morphology, surface morphology and Raman spectrogram of the diamond coating show that the thickness of the diamond coating is uniform and the quality is satisfactory. This provides reference for the application of the large-aperture diamond-coated drawing die.
Keywords: HFCVD, Large-aperture, Diamond-coated Drawing Die, Preparation System

1. Introduction

CVD (Chemical Vapor Deposition) diamond films have properties similar to those of natural diamond, such as high hardness, high thermal conductivity, good self-lubricating property and chemical stability, which make them widely used in the field of mold production [1]. Compared with traditional drawing dies, diamond-coated drawing dies not only have higher service life, higher processing quality and production efficiency, but also can effectively save strategic metal resources such as tungsten and cobalt, and realize sustainable development of industrial production.

Many researches have been carried out on the preparation of diamond-coated drawing die. In 1989, Okuzumi et al. [2] carried out a series of researches to solve the problem of adhesion between diamond coating and substrate, which laid a foundation for the following research. Murakawa et al. [3] began to use HFCVD (Hot Filament Chemical Vapor Deposition) method to deposit diamond coating on the inner wall of the wire-drawing die in 1993. The diameter of the coating die is 4.8 mm, and the excitation source is helical tantalum filament. However, during the deposition process, the hot filament becomes soft and deformed when heated to 2000 °C and deviates from the axis of the die, which leads to the uneven coating and the deposition failure. Then, they tried to weld the thick diamond film in the hole of the drawing die, successfully produced the diamond drawing die with the inner diameter less than 2mm, and then successfully conducted the drawing test with the die [4]. Thereafter, Ivan et al. [5] successfully produced the diamond coated wire-drawing die by using the MPCVD (Microwave Plasma-Enhanced Chemical Vapor Deposition) method, in which a straight copper tube was placed at the axial center of the wire-drawing die, and then the reactant gas was imported from the copper tube, so that the plasma successfully reached the inner surface of the wire-drawing die. Li et al. [6] independently developed the HFCVD diamond coating deposition equipment, which successfully deposited diamond coating on the wire-drawing die. Wang et al. [7] Conducted simulation and experimental researches on HFCVD diamond coating growth on small inner-hole surface of wire-drawing die with no filament through the hole. Zhang et al. [8]. performed several experiments to explore effects of the different types and proportions of walnut shell and diamond powders on the properties of nucleation, growth, and adhesion of diamond films deposited via HFCVD method. Lu et al.[9] studied the properties of diamond coating prepared on milling cutter and its effect on the cutting performance of stone. Compared to the uncoated cutter, the surface roughness decreases. After coating, the diamond coating on the surface of the cutter did not show obvious shedding, and the amount of wear on the back face of the uncoated cutter was consistent. Yan et al[10] researched the machining performance of hard-brittle materials by multi-layer micro-nano crystalline diamond coated tools. The multilayer coating structure shows benefits from the single layer coatings, for example, improving adhesion to the substrate and inhibition of crack propagation, while the tool life and machining stability are significantly better than the single diamond layer coated tools.

International scholars have conducted numerous researches and attempts on the application prospect of diamond coating mould [11]-[13]. However, these studies are mostly from the experimental point of view[14]-[16], the practical application is limited. Most of them are focused on the small-aperture wire-drawing die. In view of the large-scale production of large-aperture diamond-coated drawing die, although there is a great demand in the market, the production effect is not ideal, and the research progress in this area is very limited.

Therefore, this paper mainly focuses on the preparation system of diamond coating for large-aperture drawing die. According to the finite element analysis of the temperature field of the die base on HFCVD process, the HFCVD deposition system for the large aperture drawing die is designed, and the deposition effect of the system is studied experimentally, which provides a reference for the application of diamond coating on the large aperture drawing die.

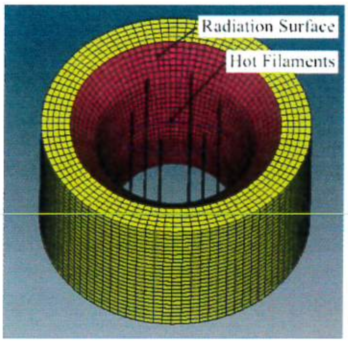
2. Finite Element Analysis of Temperature Field of Die Base under HFCVD Process

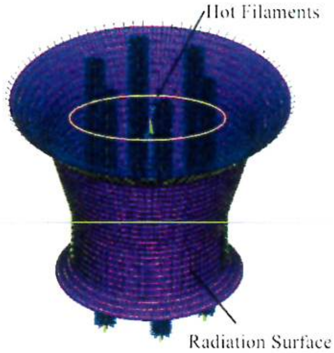
2.1. Finite Element Analysis Model

In the process of diamond deposition by HFCVD, heat transfer is mainly carried out by radiation heat transfer, and the temperature field model of pure heat radiation can be established. A three-dimensional mesh model of the drawing die with an inner diameter of 40 mm is established as shown in Figure 1. The hot filament and cemented carbide die are defined as SOLID70 element, and the surface of the hot filament and the inner surface of the die are covered with a layer of SHELL31 element as the radiation surface. The radiation matrix element of the finite element analysis software is used to calculate the thermal radiation of the hot filament and the inner surface of the die. Figure 2 shows the defined radiation surface element.

2.2. Temperature Distribution of Drawing Die Base

From Figure 3, it can be seen that the temperature in the axial direction distributes in steps, and the temperature of the inner wall at the position of the sizing belt is the largest. With the increase of the diameter of the inner wall, the distance between the hot filament and the inner wall increases gradually, while the temperature decreases gradually, and reaches the minimum at the entrance position. In the circumferential direction, the temperature varies periodically because the hot filament is symmetrically distributed around the axis, and the temperature of the inner wall is the highest at the nearest distance from the hot filament. With the increase of the distance from the hot filament, the temperature decreases gradually, and the temperature in the middle of the two hot filaments is the lowest.





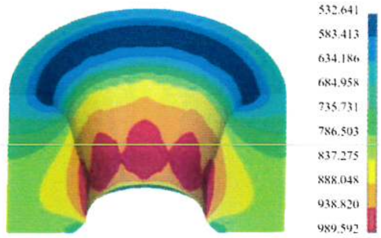


Figure 1. 3D mesh model of drawing die.

Figure 2. The hot filaments and radiation surface of the die.

Figure 3. Temperature distribution of drawing die base.

2.3. Effect of Hot Filaments Parameters on Temperature Distribution of Drawing Die Base

Based on the distribution of temperature field in the drawing die, the finite element model is changed by changing the hot filament quantity, the radius of hot filaments and the distance between hot filaments and the die, then the temperature distribution of die base under different conditions is simulated, and the appropriate process parameters of depositing diamond coating can be obtained and the design of hot filament arrangement can be optimized. Because the distribution of temperature field of the inner wall is different in circumferential direction and axial direction, the change law of temperature field should be analyzed mainly in circumferential direction and axial direction.

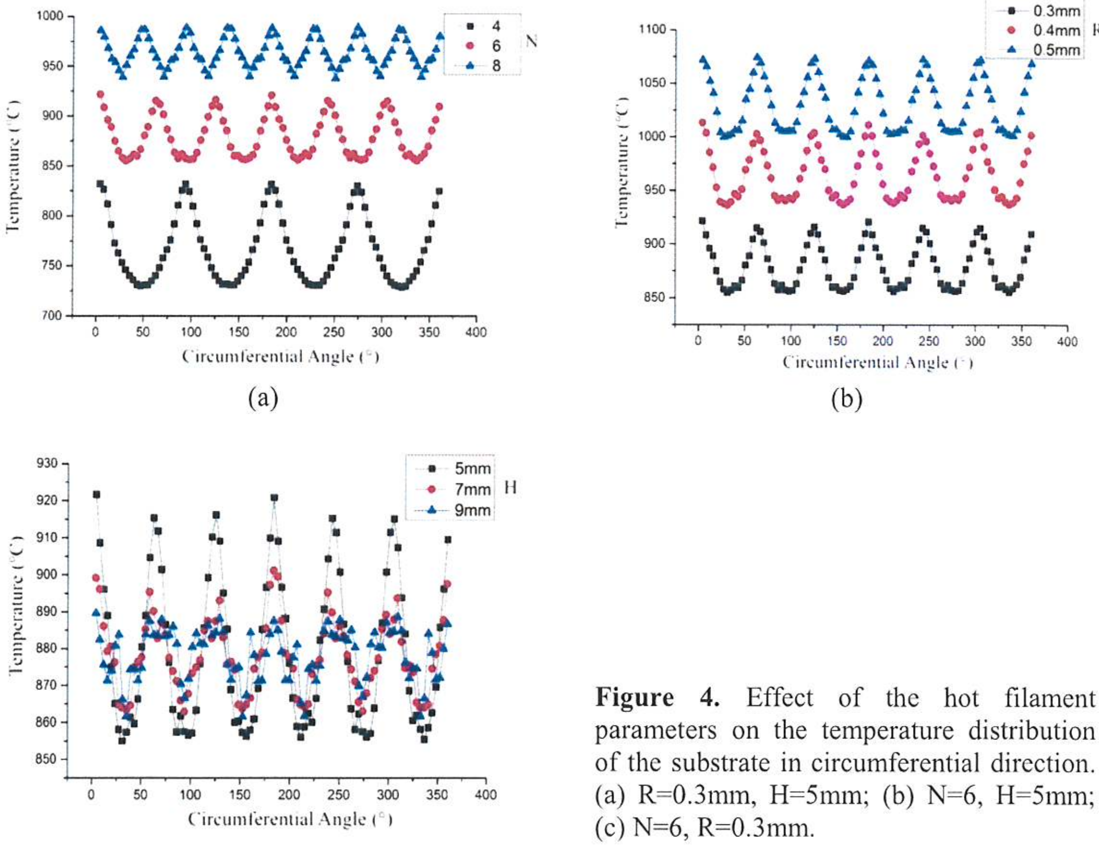


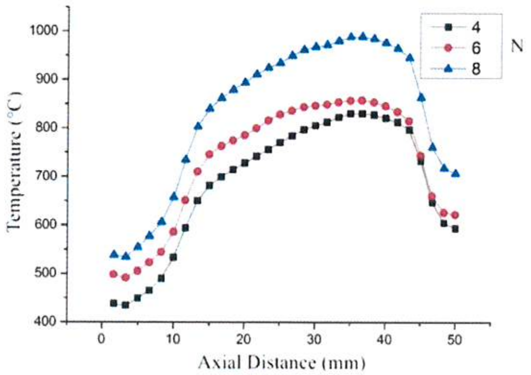
Figure 4. Effect of the hot filament parameters on the temperature distribution of the substrate in circumferential direction. (a) R=0.3mm, H=5mm; (b) N=6, H=5mm; (c) N=6, R=0.3mm.

As shown in Figure 4, it can be seen that the temperature of the inner surface of the die base changes periodically with the increase of the hot filament quantity, and decreases or increases with the change of the distance according to the cosine law. The maximum temperature difference of the inner surface of the mold is about 100 °C, 60 °C and 50 °C respectively, and the average temperature increases about 120 °C and 80 °C respectively for every increase of two hot filaments. The average temperature of the die increases nonlinearly, while the temperature difference decreases nonlinearly, which indicates that the circumferential uniformity of the substrate is increasing.

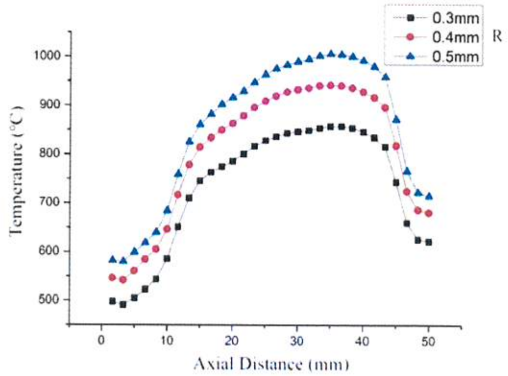
With the increase of the hot filament radius, the maximum temperature difference of the inner surface of the mold is about 60 °C, 70 °C and 75 °C respectively, and the average temperature changes by about 80 °C and 70 °C respectively. The average temperature of the inner surface tends to increase, but the temperature uniformity in the circumferential direction decreases to some extent, but the decrease is not obvious.

With the increase of the distance between the inner wall and the hot filament, the temperature peak value in the circumferential direction decreases, and the temperature distribution becomes uniform and the curve becomes smooth. The maximum temperature difference of the inner surface of the mold is about 100 °C, 55 °C and 40 °C, respectively, which indicates that the temperature uniformity has been significantly improved.

From the effect of the hot filament parameters on the temperature distribution of the axial substrate of the drawing die in Figure 5, it can be seen that the improvement of the temperature uniformity is very limited by the three factors of the hot filament quantity, the radius of the hot filament and the distance between the hot filament and the die, but the hot filament number and the radius of the hot filament can change the temperature value of the inner wall of the die.



(a)



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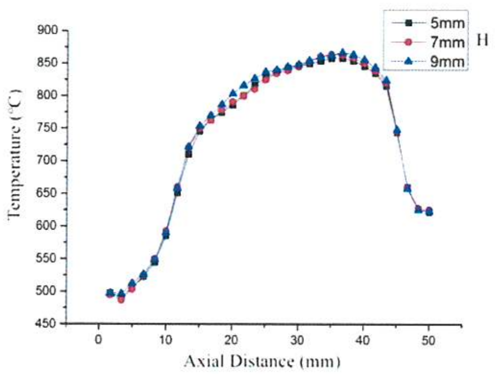


(c)

Figure 5. Effect of the hot filament parameters on the temperature distribution of the substrate in axial direction. (a) R=0.3mm, H=5mm; (b) N=6, H=5mm; (c) N=6, R=0.3mm.

In the process of depositing diamond coating by HFCVD, the temperature field of die base should be enough uniform, and the temperature should be kept between 800°C and 1000 °C. According to the above analysis, when the diamond coating is deposited on the die with 40 mm inner diameter by HFCVD, The optimal hot filament parameters are that the hot filament quantity is 6, the distance between the hot filaments and the inner surface of the drawing die is 9 mm and the radius of the hot filaments is 0.3 mm. Under these parameters, the uniform temperature field can be formed on the inner surface of the mold, and the uniform coating can be grown.

3. The Preparation System of Large-aperture Diamond-coated Drawing Die

On the basis of the study of the effect of hot filament parameters, in order to further improve the uniformity of die base temperature, the uniform relative rotational motion between hot filament and inner surface is added. As shown in figure 6, a new HFCVD coating mold preparation system with rotating U-shape groove was developed. The axis of the hot filament subassembly, the axis of the drawing die and the axis of the rotary table are coincident in the preparation process. The hot filament subassembly remains stationary and the drawing die rotates uniformly with the rotary table. So that the uniform relative movement between the hot filament subassembly and the die can be kept.

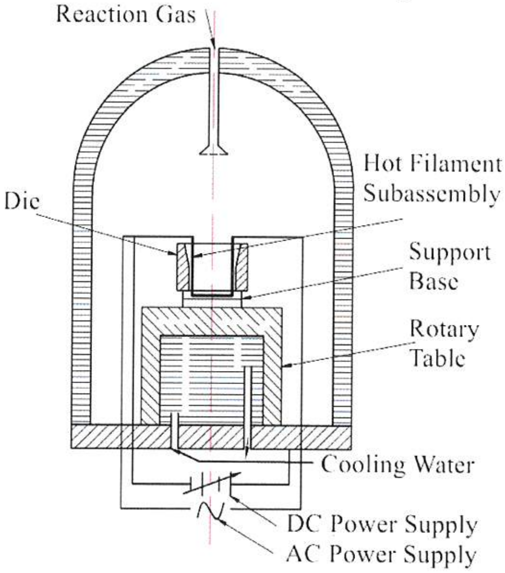


Figure 6. The HFCVD coating mold preparation system.

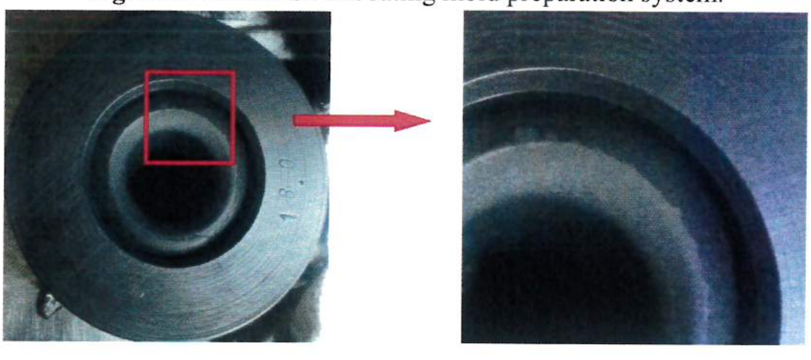


Figure 7. Diamond coating of drawing die after deposition..

4. Testing Experiment of Coating

In order to test the coating deposition effect of the large-aperture diamond-coated drawing die preparation system, the deposition experiments were carried out on the inner wall of the drawing die by HFCVD method. Figure 7 shows that the inner surface of the drawing die is uniformly coated with a layer of diamond. Scanning electron microscopy was used to detect the cross-sectional morphology and surface morphology of the coating on the inner wall of the drawing die, and Raman spectroscopy was used to analyze the surface quality of the coating.

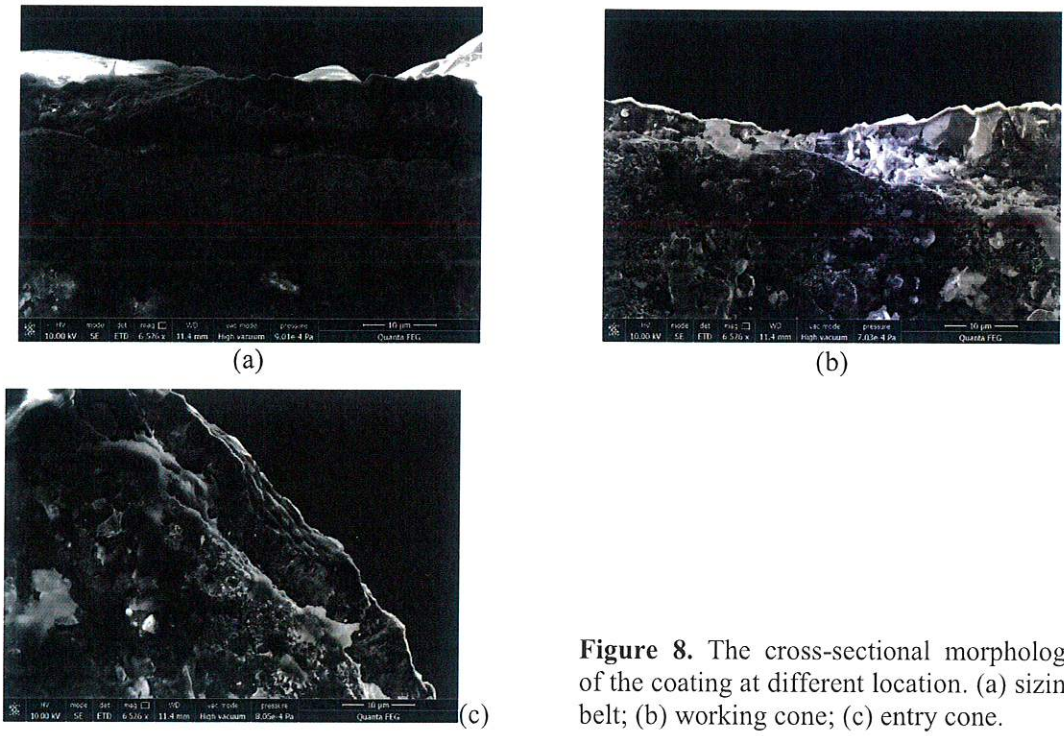
Before characterizing the surface morphology, quality and thickness of the inner wall coating at different positions of the drawing die, in order to facilitate the observation, it is necessary to prepare observation samples. We cut the sample by wire cutting, and then use ultrasonic cleaning equipment to ultrasonically clean the sample in ethanol reagent and dry it. The surface morphology, cross-sectional morphology and thickness of the coating are observed with a scanning electron microscope. Raman spectrometer is used to analyze the surface quality of the coating.

4.1. Detection of Cross-sectional Morphology of the Coating

Figure 8 shows a cross-sectional morphology of the diamond coating at different location in the hole of the drawing die. It can be seen from the figure that the coating thickness of sizing belt is the most uniform. The entry cone is curved, but the coating thickness is uniform as well. The diamond coating thickness at each position of the mold is relatively uniform, and there is an obvious interface between the coating and the substrate mold. By measurement, the average coating thickness is about 10 μm. The maximum axial coating thickness difference of the sizing belt is 0.8 μm, and the maximum circumaxial coating thickness difference is 1.3 μm, which meets the requirements of the coating thickness.

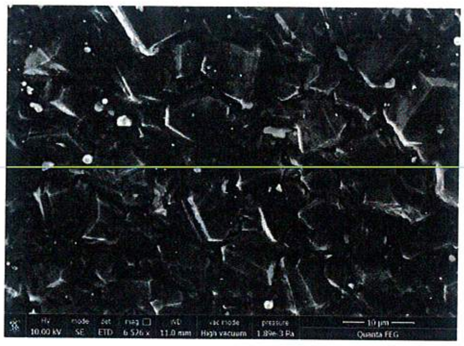
4.2. Detection of Surface Morphology of the Coating

Figure 9 is a surface morphology of the diamond coating at different locations in the hole of a drawing die. As can be seen from the figure, the surface of the CVD diamond coating is rough and the grain size is about 5 μm. The surface smoothness of the diamond coating is not ideal and cannot meet the practical production requirements because the surface is covered with big diamond grains. If this coating is used directly for production without treatment, it will have a great impact on the quality of the products. Therefore, it is necessary to carry out ultrasonic polishing on the coating for practical applications.

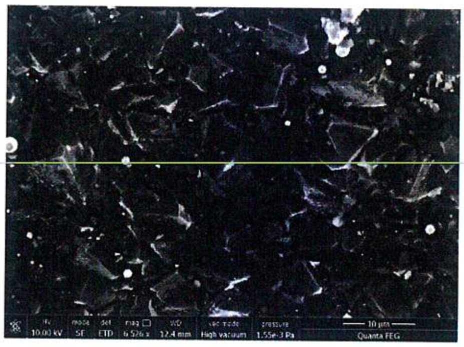


(a) (b) (c)

Figure 8. The cross-sectional morphology of the coating at different location. (a) sizing belt; (b) working cone; (c) entry cone.



(a)



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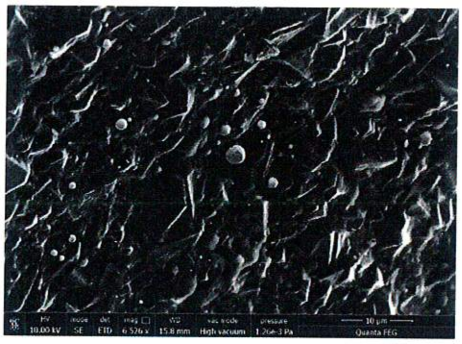

(c)

Figure 9. The surface morphology of the coating at different location. (a) sizing belt; (b) working cone; (c) entry cone.

4.3. Detection of Surface Quality of the Coatings

Figure 10 is the Raman spectrogram of the diamond coating. Red line is near the sizing belt of the mold and black line is at the working cone. It can be seen from the figure that the diamond coating on the surface of the inner hole has only one distinct characteristic peak near 1338 cm-1, which deviates little from the diamond characteristic peak 1332 cm-1, indicating the existence of a certain residual compressive stress, but the stress is not large. Which show that the main composition of the coating is sp3 structure diamond, and the high quality diamond coating can be deposited.

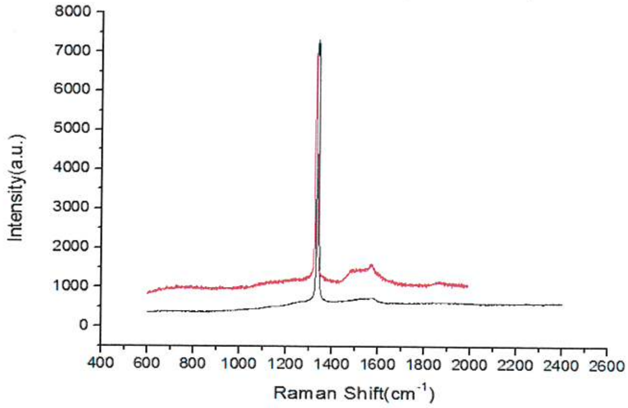

Figure 10. Taman spectrogram of the diamond coating.

5. Conclusion

(1) When diamond coating is deposited on the inner surface of carbide drawing die by HFCVD method, the temperature uniformity in the circumferential direction of the inner surface of die can be increased by increasing the hot filament quantity, decreasing the radius of hot filaments and increasing the distance between hot filaments and the inner surface of die. The distribution of hot filament have little effect on the uniformity of temperature distribution in the axial direction, but can change the temperature value of the inner surface in the axial direction.

(2) When diamond is deposited by HFCVD on the drawing die with 40mm inner diameter, the parameters of hot filament arrangement are optimized by finite element analysis. When the hot filament quantity is 6, the distance between the hot filaments and the inner surface of the mold is 9mm, and the radius of the hot filaments is 0.4 mm, the uniform temperature field can be formed on the inner surface of the die, and the uniform coating can be grown.

(3) The hot filament subassembly with U-shaped groove is used for the large-aperture drawing die, and the rotating table is used to keep the hot filament subassembly and the inner wall of the drawing die moving relatively uniformly. During this process, the axes of the rotating table, the hot filament assembly and the drawing die always coincide. On this basis, the high quality diamond coating can be deposited and the thickness of diamond coating was uniform.