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# Micro- and Nano-crystalline CVD Diamond Coated Micro Drills in the Drilling of EDM Graphite

X. L. Lei[a], L. Wang[b], B. Shen[c], F. H. Sun[d], Z. M. Zhang[e], M. Chen[f]

**Abstract:** In this investigation, micro- and nano-crystalline hot filament chemical vapour deposition (HFCVD) diamond films are successfully deposited on two-flute spiral micro drills (D=0.39 mm). After deposition, micro-crystalline diamond (MCD) and nano-crystalline diamond (NCD) coated micro drills are characterized by field emission scanning electron microscopy (FESEM), Atomic force microscope (AFM) and Raman spectroscopy. Cutting experiment involving bare WC-Co, MCD and NCD coated micro drills is conducted to test their drilling performance in graphite drilling. The drilling test results show that number of drilled holes of MCD and NCD coated micro drill is about 4-6 times more than that of uncoated one.

**Keywords:** NCD; Micro drill; Hot filament CVD; Graphite; Cutting experiment

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## Introduction

Graphite is widely used as the material of Electrical discharge machining (EDM) electrodes to shape high performance, intricate and accurate parts in leading aeronautical, automotive and moulds manufacturing companies. However, polycrystalline microstructure of EDM graphite makes it difficult to machine as random oriented graphite aggregates lead to a very abrasive powdery chip during machining [1].

Hot filament chemical vapour deposition (HFCVD) diamond thin films have been widely used as abrasive resistant material to protect cutting tools from abrasive wear [2][3]. Previous drilling studies using HFCVD diamond coatings show a threefold increase in the number of holes drilled in both printed circuit boards and aluminum work pieces when compared with uncoated tool [4].

Micro mechanical drilling is one of the micro component fabrication method for creating miniature devices and components with features that range from tens of micrometers to a few millimeters in size. But there are several challenges to overcome when scaling down drills to microscopic sizes as tool wear has greater impact on micro drills compared to macro ones. Meanwhile, any chips adhering to the drill will easily eliminate a path for chips to evacuate the cutting zone and will result in a spike in the cutting forces, leading to tool fracture because of the low flexural strength of the drills. Diamond films for micro drills are promising as its favorable mechanical and tribological properties, such as high hardness, chemical inertness, low adhesion to many materials and low friction coefficient [5]. Recently, nano-crystalline diamond coating is gaining great interest as its smooth surface betters the micro-structured counterpart for complex shape geometries, which leads to low friction coefficient between workpiece and cutting tools.

School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai, China
E-mail: [a]superlxl@sjtu.edu.cn, [b]liangwang@sjtu.edu.cn, [c]binshen@sjtu.edu.cn, [d]sunfanghong@sjtu.edu.cn, [e]zmzhang4202@163.com, [f]mchen@sjtu.edu.cn

This work consists of the evaluation of the cutting performance of Micro- and nano-crystalline CVD diamond coated micro drills in drilling of EDM graphite. The surface topography, grain sizes and quality of as deposited diamond thin films are examined by field emission scanning electron microscopy (FESEM), Atomic force microscope (AFM) and Raman spectroscopy, respectively. Then, we investigate the cutting performance of Micro-, nano-crystalline diamond coated and bare WC-Co micro drills in drilling of EDM graphite. The comparative results show that nano-crystalline diamond coated micro drills has the longest tool life, about 6 times compared to that of uncoated one.

## Experimental procedure

### Fabrication of CVD diamond coated micro drills

The WC–Co (ISO:K20) micro drills (D=0.4 mm) are used as substrates, as shown in Fig. 1. In order to avoid the catalytic effect of cobalt, enhancing the diamond nucleation and the adhesion between the coating and substrate, two-step pretreatments are adopted prior to the deposition: Firstly, dipping the substrates in the Murakami's reagent (10 g $K_3[Fe(CN)]_6$+10 g KOH+100 ml $H_2O$) in an ultrasonic vessel for 8 min. Secondly, etching substrates with Caro's acid (30 ml $H_2SO_4$:70 ml $H_2O_2$) for 60 s. Murakami's reagent attacks WC grains and roughens the substrate surface; as while, Caro's acid oxidizes the binder to soluble $Co^{2+}$ compounds, thus reducing the surface cobalt concentration.

The deposition process is conducted in a home-made bias-enhanced HFCVD apparatus. Acetone, $H_2$ and argon are used as reaction gas. Detailed deposition parameters are listed in Table 1. The introduction of Ar during NCD film deposition could increase second nucleation of grains which makes diamond grains finer.

**Table 1 Deposition parameters of MCD and NCD films**

| | MCD films | NCD films |
|---|---|---|
| Acetone concentration (%) | 0.8-1.2 | 1.8-3 |
| Pressure (Torr) | 35-40 | 5-15 |
| Filament temperature (℃) | 2000-2200 | 2000-2200 |
| Deposition temperature (℃) | 800-900 | 800-900 |
| Bias current (A) | 3.5 | |
| Deposition time(h) | 3.5 | 4 |
| Ar concentration | | > 90% |

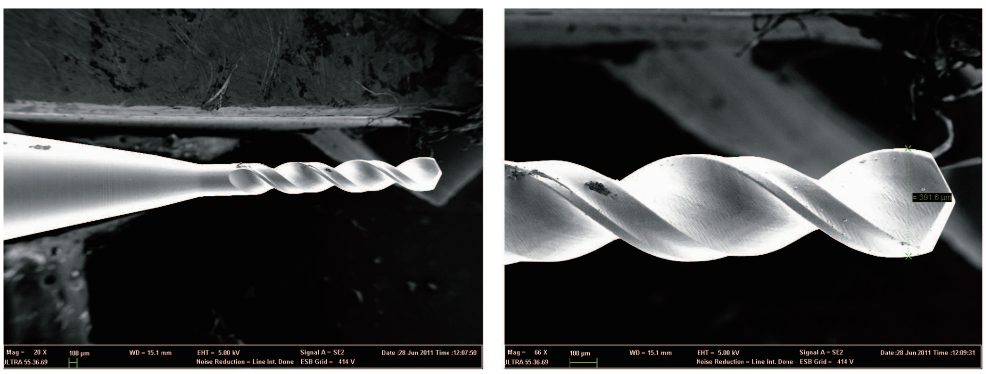


Fig. 1 SEM images of the micro drill

### Drilling tests

In order to investigate cutting performance of as fabricated MCD and NCD coated micro drills, comparative drilling tests are conducted for both diamond coated and bare micro drills on a CNC graphite machine. The workpiece is cuboid shaped high purity EDM graphite of grade ISO-68 (Toyo Tanso Inc.). Suction tubes are applied during machining to suck up graphite powders. The spindle speed and feed rate are 12500 r/min and 200 mm/min, respectively.

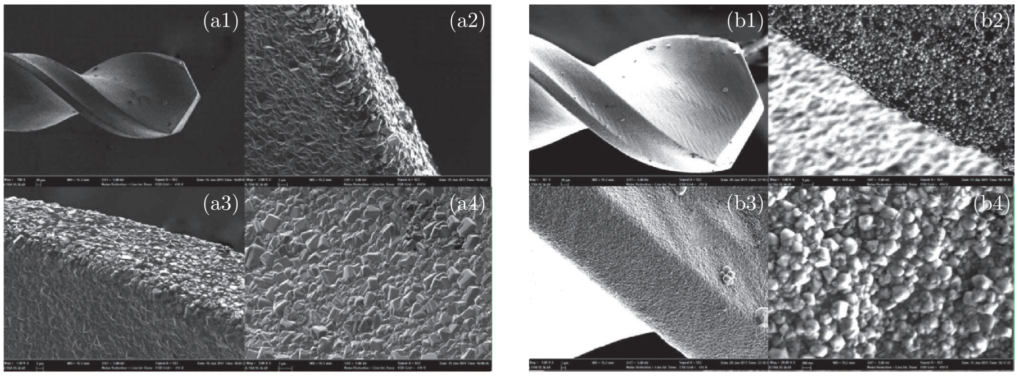
## Results and discussion

### Characterization of diamond coated micro drills

FESEM is employed to observe surface morphologies of MCD and NCD films clearly and exactly. Fig. 2 shows different parts of as-fabricated diamond coated micro drills. It can be seen that a continuous layer of diamond crystallites is uniformly coated on different locations of micro drills. As argon gas promotes secondary nucleation of diamond grains during NCD deposition process, grain size of NCD films is about 200-300nm while that of MCD films is about 2-4 um. Meanwhile, most MCD grains have sharp octahedral shape and exhibit <111> crystallographic orientations. Comparatively, the crystallographic orientations of grains on NCD film is not so apparent.

The local roughness of fabricated MCD and NCD coated micro drills is measured within a 20 μm×20 μm and a 10 μm×10 μm area using an AFM. The average surface roughness (Ra) of MCD and NCD coatings is

279.3 nm and 91.35 nm, as shown in Fig. 3. As tool surfaces of micro drills are not grinded, the local roughness measured by AFM is sensitive to the texture created by the diamond facets, that's one reason why we use different growth conditions in CVD procedure to deposit smaller NCD grains.




(a) MCD coated micro drills

(b) NCD coated micro drills

Fig. 2 FESEM images of ($a_1$, $b_1$) drilling parts; ($a_2$, $b_2$) major cutting edge; ($a_3$, $b_3$) minor cutting edge; (a4,b4) plane of as-deposited diamond coated micro drills

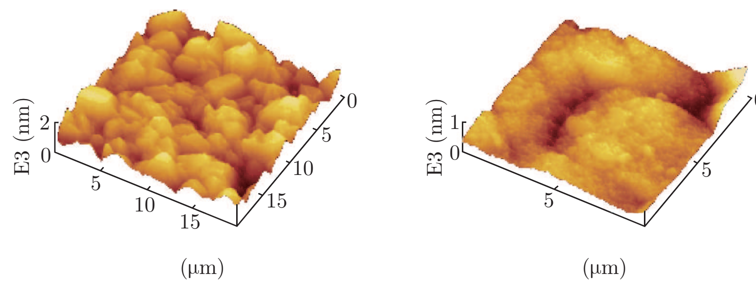



Fig. 3 Three-dimensional topography view of a representative MCD (left) and NCD(right) coating.

Raman spectroscopy is adopted to determine the surface quality for as-deposited MCD and NCD films, as plotted in Fig. 4. The Raman spectra of MCD film shows a sharp peak located at 1332 cm$^{-1}$ (diamond peak) and no other obvious peaks, which reveals high purity and excellent quality of the diamond thin film. There are two wide peak at 1350 (D peak) and 1580 (G peak) cm$^{-1}$ in raman spectra of NCD film which is related with the sp$^2$ C-C bonding. The sharp peak at 1332 cm$^{-1}$ is the characteristic line of crystalline diamond and wide enough to overlap with the D peak. Meanwhile, the peak at 1140 cm$^{-1}$ is also visible, which is assigned to the nano-crystalline diamond or disordered sp$^3$ carbon phase. The absence of sp$^2$ C-C bonding between diamond grains would lower the hardness of NCD film to some extent.

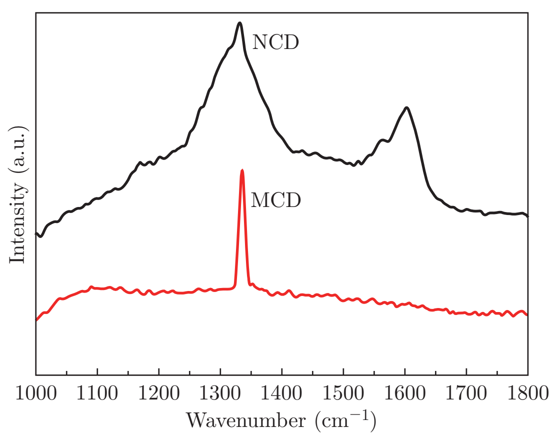



Fig. 4 Raman spectrum of the MCD and NCD films.

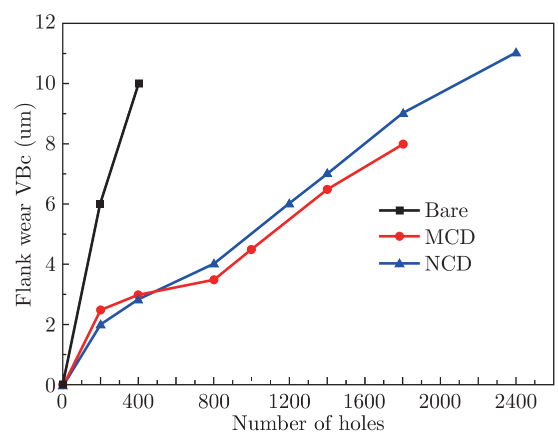



Fig. 5 Maximal flank wear of main drilling flutes of micro drills.

**Results of drilling tests**

Although common graphite is easily cut material, EDM graphite should own enough strength to avoid the destruction during EDM process. Meanwhile, the specific shape of electrode (thin wall, small fillet etc.) proposed higher request of strength and grain size of EDM graphite electrode, which leads that cutting tools are easily abraded during machining. That is why diamond coated micro drills are promising to cut EDM graphite as the high hardness, chemical inertness, low adhesion to many materials and low friction coefficient of diamond films.

Comparative drilling test results show that diamond coated micro drills could drill about 2000 holes, 4-6 times more than that of bare WC-Co micro drills when maximal flank wear of main drilling flutes is all about 10um, as shown in Fig. 4. Fracture of drilling part of MCD coated micro drill is happened during drilling 1800 to 2000 holes. When comparing drilling results of MCD and NCD coated micro drills, it is observed that while drilled holes less than 500, the VBc of main drilling flute of MCD coated micro drill is larger than that of NCD coated one; the contrary is the case while drilled holes more than 500. The reason is in the first drilling period, friction between cutting tool and graphite is the main factor to cause flank wear, then the influence of hardness of diamond film becomes dominate as MCD and NCD films are both polished by random graphite polycrystalline aggregates. The results of comparative drilling tests is of benefit to further extend the application of MCD and NCD material in micro-scale.

## Conclusions

Two kinds of diamond films, called MCD and NCD films are successfully deposited on micro drills using HFCVD method and characterized by FESEM, AFM and Raman spectroscopy. Then cutting experiment involving MCD, NCD coated and bare WC-Co micro drills is carried out in machining of EDM graphite. The result shows diamond films can properly protect cutting flutes of micro drills from abrasive wear as its superior properties. Consequently, tool life of diamond coated micro drills is about 4-6 times than that of uncoated ones. Different maximal flank wear rate of MCD and NCD coated micro drills is analysed due to slight differentiation of hardness and friction coefficient of MCD and NCD films.

## Acknowledgements

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## References

[1] F. A. Almeida, J. Sacramento, F. J. Oliveira and R. F. Silva: Surf. & Coatings Technol. Vol. 203(2008) , p. 271-276.

[2] F. H. Sun, Z. M. Zhang, M. Chen and H. S. Shen: Diamond Relat. Mater. Vol. 12(2003), p. 711-718.

[3] B. Shen, F. H. Sun, H. G. Xue, M. Chen and Z. M. Zhang: Surf. Eng. Vol. 25(2009), p. 70-76.

[4] H. Sein, W. Ahmed, M. Jackson, R, Woodwards, R. Polini: Thin solid films. Vol. 447-448(2004), p. 455-461.

[5] C. D. Torres, P. J. Heaney, A. V. Sumant, M. A. Hamilton, R. W. Carpick and F. E. Pfefferkorn: Int. J. Mach. Tools Manuf. Vol. 49(2009), p. 599-612.5.