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Cutting Performances of Nanocrystalline Diamond Coated Milling Tools in Machining Graphite

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Abstract: In this study, diamond films are deposited by using hot filament chemical vapor deposition (HFCVD), Nanocrystalline diamond (NCD) coated cemented tungsten carbide (WC-Co) milling tools are characterized, compared with microcrystalline diamond (MCD) and composite diamond coated ones, in terms of morphology with field emission scanning electron microscope (FESEM). Moreover, the diamond coated tools are evaluated in machining graphite materials. The results show that the NCD and composite diamond coated tools have smoother surfaces than the MCD coated tools because of the smaller grain size. In milling tests, diamond coated tools allow to be give a higher wear resistance and longer tool life, when compared to bare WC-Co milling tools. Coating delamination is noted as the major tool failure mode for MCD and composite diamond coated cutting tools, but the NCD exhibit a better adherent strength to the substrate, and consequently improve the tool life by a factor of 6 than that of uncoated milling tools.

Keywords: Hot filament chemical vapor deposition (HFCVD); Nanocrystalline; Composite; Cutting performances; Graphite

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Introduction

Graphite is wildly used in semiconductor and solar cell industry due to its good electrical conductivity, but it is difficult to machine because of abrasive powdery chip result from the random oriented graphite aggregates. The tool is prone to suffer a severe wear during machining graphite, thus lead to low production efficiency [1]. Nowadays, milling of graphite should using coated carbide mills is acceptable in the industries fields. Diamond coating is a good solution in this application for its excellent properties such as high hardness and wear resistant, good thermal conductivity and low friction [2].

It has bad finish of machining surface when using the conventional microcrystalline diamond (MCD) coated tools, although MCD films have high wear resistant. The surface roughness of diamond films is one of the key factors determining the machining finish. Usually, the larger the grain size of the diamond film, the higher the surface roughness for the film. Nanocrystalline diamond (NCD) film has a surface with relatively low roughness, but also a low wear resistant [3,4].

In this study, NCD, composite diamond films which are consisted of a layer of NCD onto a layer of MCD are fabricated in HFCVD apparatus. The surface morphology of the diamond films are examined using field emission scanning electron microscope (FESEM). Moreover, the cutting performances of the coated mills, comparing with uncoated ones, are investigated in machining graphite materials, and tool microscopy is applied to identify the wear mechanisms of the coated and uncoated milling tools.

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Experimental

Fabrication of diamond coated endmill. WC-6%Co endmills are employed as substrates, which is submitted to two-step chemical etching pretreatment to facilitate the diamond growing. Firstly, the WC-Co substrates are roughen by ultrasonic agitation in the Murakami's reagent (10 g $K_3[Fe(CN)]_6$+10 g KOH+100 ml H_2O) for 20 min, then, the Caro's acid (30 ml H_2SO_4: 70 ml H_2O_2) is employed to etch the cobalt element existed on the substrate surface for 30 s. Murayama's reagent attacks WC grains and roughens the substrate surface, thus, favoring the adhesion of the diamond coating by mechanical interlocking; the choice of the Caro's acid is made due to its well-known strong reactive etching affinity towards cobalt element, Caro's acid oxidizes the binder to soluble Co^{2+} compounds, thus reducing the cobalt concentration [5]. Nanocrystalline diamond films are deposited on the endmills by HFCVD processes. Acetone and hydrogen are adopted as reactive gases. Two triple-twisted tantalum wires spacing 40mm are used as gas activators and are set 10 mm above the endmills. The filament temperature and substrates temperature are ∼2000℃ and ∼800℃, respectively. In order to guarantee the adhesive strength, half an hour of diamond nucleation is performed under the conditions of chamber pressure of 1.6 KPa, H_2 flow rate of 200 sccm and acetone flow of 80 sccm. This nucleation stage is as same as that in conventional microcrystalline diamond film depositing process. Argon with a flow rate of about 250 sccm is added in the growth stage to produce nano-structured coatings. In this stage, lower chamber pressure and acetone flow rate are adopted, and the values are set to be 1.3 KPa and 70 sccm, respectively. The composite diamond films are obtained by deposit a layer of NCD film onto the conventional MCD film. The detailed deposit parameters are list in Table 1.

Table 1 Deposition parameters

	MCD		NCD	
	nuclear	growth	nuclear	growth
Carbon/H_2/Ar flow [sccm]	70/200/0	60/200/0	80/200/0	70/200/250
Pressure [KPa]	1.6	3.3	1.6	1.3
Filament temperature [℃]	1500-2000	1500-2000	1500-2000	1500-2000
Substrate temperature [℃]	800-900	800-900	800-900	800-900
Deposition time [h]	0.5	4	0.5	4

For characterization, filed emission scanning electron microscopy (FESEM) is used to observe the morphology, microstructure and grain size of as-deposited diamond films.

Milling tests. The cutting performance of diamond coated endmills is evaluated by dry milling of graphite materials. The tests are conducted on a CNC high speed Graphite Engraving Machine (LT-650E). High power vacuum is adopted to extract the dust and powdery chips. The milling parameters are set as follow: rotational speed of 13000 RPM; depth of cut of 0.3 mm; feed rate of 3500 mm/min. For comparison, bare WC-Co endmills are also adopted in the milling test under the identical conditions. The wear land on the end flute is observed and measured by tool microscopy.

Results and discussion

Characterization of diamond coated end mills. The MCD and NCD can be easily discern because of their distinct grain size form the SEM image shown in Fig. 1. MCD display a rugged morphology and a polycrystalline structure which are predominant in ⟨111⟩ orientation. The average grain size of MCD is the range of 1 to 3 μm. While in the case of NCD, it present a very even morphology, and it is uniform over the entire surface, the added Ar gas effectively inhibite the grownth of diamond crystal to the micrometer scale and promote the secondary nucleation. Consequently, the fine-grained diamond crystalline range in 30 to 80 nm is obtained as shown in Fig. 1(b), the inset shows a lareger magnification of the NCD surface and reveal that the grain size is about 30–80 nm. The composite diamond filmf present a typical cauliflower morphology, the surface is also consist of fine grained diamond film, as shown in the inset of Fig. 1(c). Because the outlayer NCD film can duplicate the morphology of inlayer MCD film, it shows a rougher surface than than of NCD.

Cutting performance. In the machining of graphite, cutting tools will surfer abrasive wear. The wear values of NCD, composite diamond and MCD coated and uncoated endmill are plotted in Fig. 2 as a function of cutting length. Figure 3 shows the images of uncoated and MCD, NCD and composite diamond coated endmill after the machining process. There scarcely have graphite adhere to the cutting edge; it reveals that the wear mode for all four types cutting tools is abrasion induced by the powdery graphite.

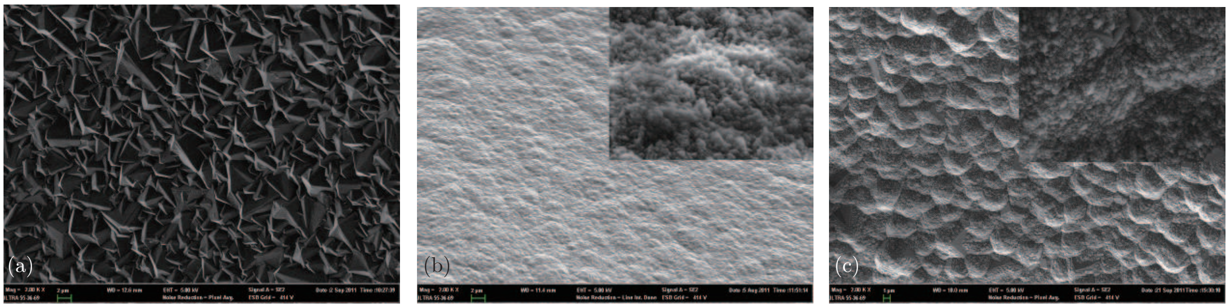

Fig. 1 FESEM images of (a) MCD and (b) NCD (c) composite diamond films on the rake face of the coated endmills.

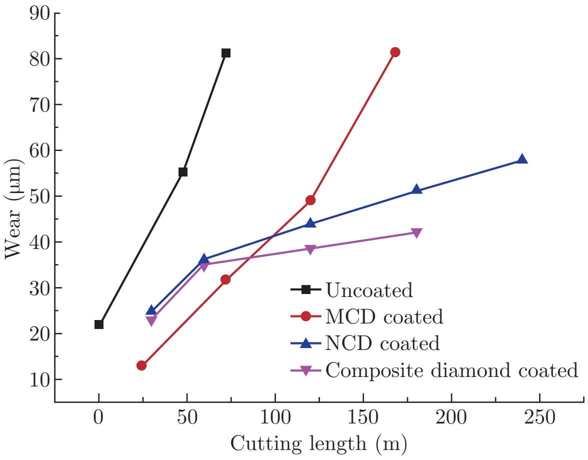

Fig. 2 The wear of NCD, MCD, composite diamond coated and uncoated endmill.

The uncoated milling tools suffer a severe wear; it reaches 81 μm after machining 72 m. In the case of MCD coated mills, they show a lower wear than that of NCD and composite diamond coated mills in the early cutting stage. This can be attributed to that the hardness of MCD is higher than that of NCD due to their different microstructure. The MCD is mainly composed of well facet crystal, while the NCD consist of nanoparticles embed in amorphous carbon. Thus, the MCD coated endmills display better wear resistant. While it surpasses the wear of NCD and composite diamond at about 120 m machining, and then sharp wear growth is detected, it reaches 82 μm after machining 168 m. This wear behavior may be caused by the film delamination as shown in Fig. 3(b), and exposed WC–Co cutting edge would experience harsh wear, as what happened in the case of uncoated milling tool.

Both NCD and composite diamond coated mills show a steady wear behavior, they undergo a similar wear process, in the first 60 m cutting, they present a very close wear value, and then composite diamond coated mills show a lower wear growth. The composite diamond film is composed of a layer of NCD on the MCD. When the NCD is wear out, the MCD underneath keep on bear the abrasive wear. Unfortunately, premature coating delamination occurs for composite diamond coated endmill at about 180 m with an end flute wear-land of 42 μm, as shown in Fig. 3 (d), hence we select the time of coating failure to dictate the tool life of composite diamond coated tools, rather than the abrasive wear of the composite diamond. The wear of NCD coated ones is only 58 μm after machining of 240 m. The tool life of the NCD coated mill is roughly 6 times more than that of the uncoated one, if selects 58 μm as the tool wear criterion. It indicate that NCD coated mills give an excellent cutting performance, the extremely abrasive behavior of graphite leads to a sharp tool wear growth and a shortened tool life for tools without coating.

The different failure form of MCD and composite diamond to NCD coated endmill can be attributed to their different surface microstructure. The MCD shows a rougher surface, which also offered by composite diamond coated mill on the condition that the NCD films

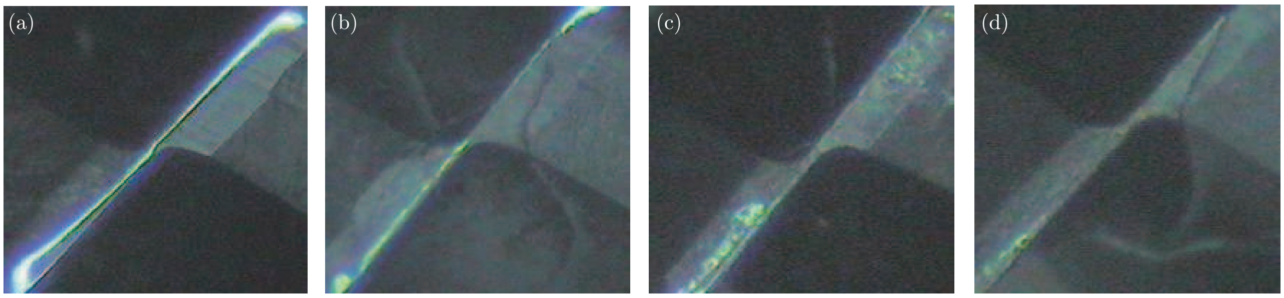

Fig. 3 Images of (a) uncoated, (b) MCD coated, (c) NCD coated and (d) composite diamond coated endmills after machining tests.

on the surface are worn off, resulting in a larger friction coefficient, consequently larger cutting force; consequently, the adhesive strength of MCD to the substrate cannot stand the crush of graphite grains, while the NCD coated endmill possess a very smooth surface and thus a smaller friction coefficient, the shear force on the surface of coating is somewhat released. So coating peeling off did not occur when using the NCD coated tools.

Conclusions

Nanocrystalline diamond films are deposited on the cemented carbide endmills by using HFCVD method, The FESEM study shows a very smooth diamond film, with the grain size of 30-80 nm, is uniformly deposited on the substrate surface.

To evaluate the cutting performance of the fabricated diamond coated tool, comparative milling tests are conducted for NCD, MCD, composite diamond coated and uncoated WC–Co milling tools, with graphite materials as the workpiece. The results indicate that the NCD coating is of high adhesion to the substrate and wear resistance. While the composite diamond and MCD coated diamond films tend to peel off because of the high friction coefficient induced by the rough surface, but the composite diamond films present a lowest wear values during the cutting process. Endmills coated with NCD films, namely NCD and composite diamond coated endmills, show a longer life and lower flank wear compared with MCD coated and uncoated WC-Co milling tools. The research results are of great significance for high efficiency and quality machining of graphite materials.

Acknowledgements

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