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Fabrication of nt-CBN micro cutting tool

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Abstract
Nanotwinned cubic boron nitride (nt-CBN) not only possesses a considerably higher hardness than polycrystalline cubic boron nitride(PCBN), but also has more excellent fracture toughness and better high-temperature stability than natural diamond. Obviously, nt-CBN will become a new promising cutting tool for ultra-precision machining with high-accuracy and low wear rate. In this paper, the fabrication of nt-CBN micro cutting tool by using focused ion beam (FIB) milling technique was investigated through simulation analysis and experimental study. The sputtering yield and subsurface damage were first analyzed through simulation. For FIB milling nt-CBN, it is suitable to set ion energy from 10keV to 30KeV. Additionally, subsurface damage caused by FIB milling was less than 30nm, which proves that FIB milling technique is a preferable choice to machining nt-CBN material. Finally, a circular arc nt-CBN micro tool with a corner radius about 14μm was fabricated through FIB milling tests. The results show micro cutting tool has a very sharp cutting edge with blunt round radius less than 60nm as well as good milling quality with roughness less than 10nm on rake face and flank face near the cutting edge.

Nt-CBN, FIB milling, sputtering yield, subsurface damage, micro cutting tool

1. Introduction

Ultrahard nanotwinned cubic boron nitride (nt-CBN) is a new-type CBN tool material synthesized from a kind of special prepared BN precursor nanoparticles under high temperature(～1800℃) and high pressure(～15GPa)[1]. As nt-CBN presents the special nanotwinned structure with the thickness less than 5nm, it not only possesses a considerably higher hardness than polycrystalline cubic boron nitride(PCBN), but also has more excellent fracture toughness and better high-temperature stability than natural diamond. Obviously, nt-CBN will become a new promising cutting tool for ultra-precision machining with high-accuracy and low wear rate, especially for direct cutting of hardened steel. Therefore, it is necessary to study the fabrication of nt-CBN cutting tool. In view of the high hardness of nt-CBN, machining this new tool material is really a challenging issue.

In this paper, the fabrication of nt-CBN micro cutting tool by using focused ion beam (FIB) milling technique was investigated through simulation analysis and experimental study. nt-CBN sample used in this study has a hardness of 85GPa Hv and grain size in the range of 50nm ~120nm.

2. Simulation of nt-CBN by FIB technique

MonteCarlo simulation was used to simulate the sputtering process of nt-CBN sample based on the software of SRIM (Stopping and Range of Ion in Matter). According to experimental details of FIB milling, gallium ions were chosen as incident ions to simulate ion beam sputtering and its energy was set in the range of 5keV~50keV. During simulating, the number of incident ions was set as 1 000 in order to gain steady sputtering yield and short computation time. The physical parameters of nt-CBN is shown in Table 1.

Table 1 physical parameters of nt-CBN target

atom	atomic number	atomic mass(amu)	displacement energy(eV)
B	5	10.81	25
N	7	14	28
atom	lattice binding energy(eV)	surface binding energy(eV)	density (g/cm^3)
B	3	5.73	3.48
N	3	2	

2.1. Sputtering yield analysis

Sputtering yield is mainly decided by incident ion energy and incident angle in ion beam sputtering[2,3].

The operating voltage of FIB milling system, i.e., incident ion energy, was usually set in the range of 5keV~50keV. Lower incident ion energy will result in lower sputtering efficiency, while higher incident ion energy cannot be made full use. Thus, it is necessary to study suitable ion energy range for nt-CBN. When the ion energy ranges from 5keV to 50keV, the curve of sputtering yield is shown in Figure.1. The increase of ion energy makes the sputtering yield of B and N largen observably, when ion energy is lower than 30keV. However, the sputtering yield remains within a very small scope or even decreases slightly, as the ion energy is higher than 30keV. Therefore, during FIB milling nt-CBN, it is appropriate to set ion energy from 10keV to 30KeV. Lower ion energy can be applied for precision milling with low efficiency, while higher ion energy means high efficiency suitable for coarse milling of nt-CBN.

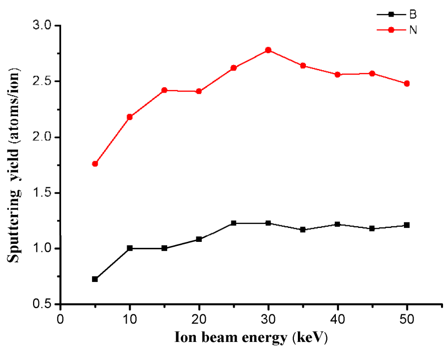

Figure 1. The relation between sputtering yield and ion energy

Previous research shows the incident angle in the range of 80°~90° is too large to generate acceptable sputtering yield under reaction of Coulombic force caused by target atoms. Therefore, the incident angle less than 80° was only studied through simulation. As shown in Figure 2, under different ion energy, sputtering yield all increases with the increasing of incident angle for B and N. It is worth noting that the sputtering yield goes up fast as incident angle increases from 60° to 80°. This result can be used to guide the FIB milling experiments.

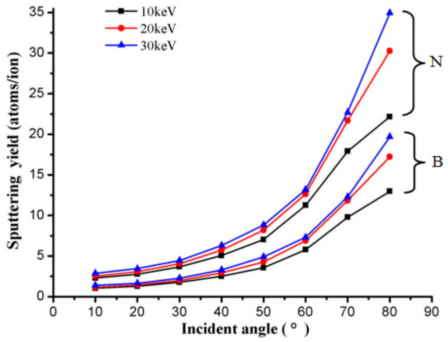

Figure 2. The relation between sputtering yield and incident angle for atomic boron(B) and atomic nitride(N).

2.2. Subsurface damage analysis

When the target was exposed to ion beam sputtering, subsurface damage within the target was inevitably generated in the forms of vacancy and replacement collision, where the main damage form is vacancy. In the simulation, it is assumed that incident ion beam was in the density of 10^{15} ION/cm^2, and then vacancy density can be calculated according to simulation result, as shown in Figure 3.

With the increase of ion energy, subsurface damage layer will gradually become deeper. On the other hand, the maximum of vacancy density increases only for ion energy ranging from 5keV to 15keV. In general, maximum depth of subsurface damage, where vacancy density gradually decreases to zero, is less than 30nm under the ion energy suitable for precision FIB milling. It indicates that subsurface damage layer caused by ion beam sputtering is not too deep to impact the cutting performance of nt-CBN micro tool. Therefore, FIB milling technique is a preferable choice for fabrication of nt-CBN cutting tool.

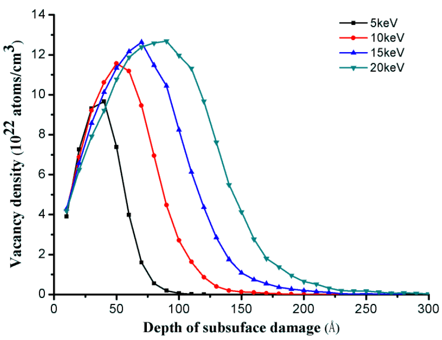

Figure 3. Vacancy density beneath the sputtered surface

3. Experimental results for FIB milling nt-CBN micro tool

In fact, FIB milling technique can form high precision tool contour, but extremely low milling efficiency is an unsolvable problem[4]. Thus, before FIB milling process, nt-CBN sample was first prepared by using Femtosecond laser machining to make primary tool contour similar to rectangular pyramid in maximum thickness of 200μm~250μm. For the triangular rake face, nose angle is about 80°.

The experiments was carried out in a FIB milling system (Quanta™ 3D DualBeam™ made by FEI). FIB milling process were shown in Figure 4. Side surface of cutting tool was formed through step1, and then step2 and step 3 were carried out to form flank face and rake face. The ion beams used for rough milling and precision milling were respectively 20nA and 1nA, as well as ion beam energy of 20keV was set for all the experiments.

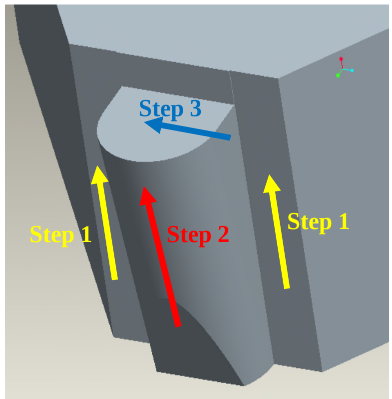

Figure 4. Machining trace of FIB milling

Figure 5 shows the finished circular arc micro cutting tool with a corner radius about 14μm. Both rake face and flank face near the cutting edge are very smooth with surface roughness lower than 10nm. Besides, it can be seen the cutting edge is sharp enough for ultra precision cutting and the blunt round radius of cutting edge was less than 60nm on the basis of measuring results.

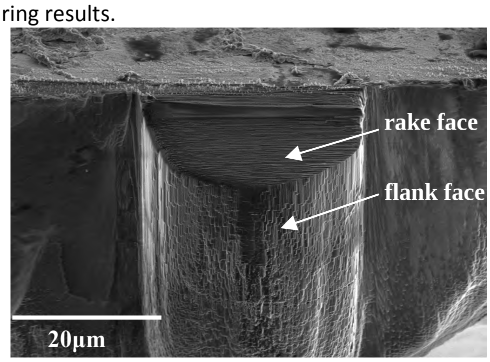

Figure 5. finished nt-CBN micro cutting tool

4. Summary

Fabrication of nt-CBN micro cutting tool was studied by simulation and experiments. The results indicate it is appropriate to set ion energy from 10keV to 30KeV for FIB milling nt-CBN, as well as subsurface damage caused by FIB milling was less than 30nm. Through FIB milling experiments, a circular arc nt-CBN micro cutting tool was fabricated with a sharp cutting edge and high surface quality.

Acknowledgements

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