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Study on material remove mechanism of ultrahard nt-CBN in mechanical lapping

Junyun Chen[1*], Tianye Jin[2], Jinhu Wang[3], Qingliang Zhao[3]

[1]College of Vehicles and Energy, Yanshan University, Qinhuangdao, +86-150001, China
[2]College of Mechanical Engineering, Yanshan University, Qinhuangdao, +86-150001, China
[3]Center for Precision Engineering (CPE), Harbin Institute of Technology, Harbin, +86-150001, China

Email：sophiacjy@ysu.edu.cn

Abstract

Ultrahard nanotwinned cubic boron nitride (nt-CBN) is a new-type CBN tool material synthesized from a kind of special prepared BN precursor nanoparticles. As nt-CBN possesses a nanostructure featuring fine twin domains of average thickness 3.8nm, its hardness is extremely high up to 100Gpa (Hv). Besides, the large fracture toughness of 12MPa m$^{1/2}$ and high oxidization temperature of 1294°C will make nt-CBN a most promising tool material especially for cutting hardened steel. However, considering extremely high hardness, machining nt-CBN into a cutting tool with high precision is indeed a new challenge. Therefore, mechanical lapping of nt-CBN was studied in this paper to analyse the material remove mechanism as well as its machinability. The cross-section topography of nt-CBN sample was first analysed for confirming integrity of internal structure and its feature size. On the basis of mechanical property of nt-CBN and fracture mechanics, a theoretical formula of critical lapping depth was given for nt-CBN. Through theoretical calculation, the critical lapping depth up to 155nm was achieved, which is considerably larger than natural diamond. Higher critical lapping depth for nt-CBN means better machinability, as ductile grooves on smooth surface can be formed as long as lapping depth is lower than the critical value. Then, mechanical lapping tests were carried out for nt-CBN with coarse diamond grains and fine diamond grains, respectively. Coarse grains resulted in most material removed in brittle region, while ultra-smooth surface with surface roughness Ra less than 5nm was formed with fine grains due to material remove completely in plastic region.

Nt-CBN, mechanical lapping, material remove mechanism, critical lapping depth

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]. nt-CBN sample in this research is about 2mm in diameter and possesses a very high hardness of 85GPa Hv. The grain size within nt-CBN is in the range of 50nm ~120nm, as shown in Figure 1, which is larger than that of ng-CBN (ABNNC)[2]. However, each grain has nanotwinned structure with the thickness less than 5nm, thus sliding dislocations can be largely restrained, which results in larger fracture toughness of 12MPa m$^{1/2}$ and higher oxidization temperature of 1294°C for nt-CBN as compared to ng-CBN. However, due to excellent mechanical property, machining this new material is indeed a large challenge. Aiming to fabricate a nt-CBN cutting tool, the mechanical lapping on nt-CBN was studied in terms of material remove mechanism through theoretical calculation and experimental analysis.

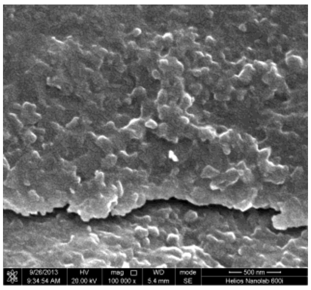

Figure 1. Cross-section topography of nt-CBN imaged by SEM

2. Theoretical analysis of material remove mechanism of nt-CBN

Lapping process of brittle material can be regarded as a combination of impression and scratching by a single abrasive grain[3]. During the impression of brittle material using a diamond indenter, if the cracks are not more than 10%, critical depth can be expressed as:

$$a_c = 0.15\left(\frac{E}{H}\right)\left(\frac{K_{IC}}{H}\right)^2 \tag{1}$$

where a_c is critical depth, E is Young's modulus (MPa), K_{IC} is static fracture toughness (MPa m$^{1/2}$) and H is hardness (MPa)[4].

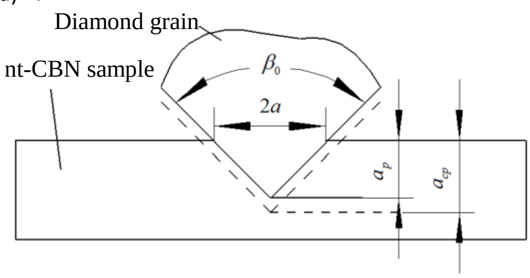

Figure 2. Dynamic interaction between diamond grain and nt-CBN sample in lapping

As shown in Figure 2, two faces, but not four faces of rectangular pyramid diamond indenter are effective to the workpiece during lapping. It is defined that a_{cp} is the dynamic critical lapping depth, 2a is the feature size of the indenter and

β_0 is the corner angle of abrasive which is assumed as 90° here。Then, the dynamic load applied by the abrasive grain P_r can be calculated as:

$$P_r = \frac{1}{2} P = \frac{1}{2} \alpha H a^2 \quad (2)$$

where P is static load of a diamond indenter in indentation test and α is the geometrical factor of an indenter (α =1.8544).

The critical dynamic load P_{cd} can be shown as the following equation[3,5]:

$$P_{cd} = \lambda_0 K_{ID} (K_{ID} / H)^3 \quad (3)$$

where λ_0 is the comprehensive coefficient, K_{Id} is dynamic fracture toughness (MPa m$^{1/2}$) and $K_{Id} = 0.3 K_{IC}$ for brittle material[4].

Then the critical depth of brittle-ductile transition can be calculated as long as $P_r = P_{cd}$. a_{cp} can be expressed according to equations (2) and (3).

$$a_{cp} = \sqrt{\frac{2\lambda_0}{\alpha}} (\frac{0.3 K_{Ic}}{H})^2 \cot(\frac{\beta_0}{2}) \quad (4)$$

For nt-CBN, the static fracture roughness K_{IC} =12.7MPa m$^{1/2}$, the nanohardness equals 98.5GPa and the average Young's modulus is 1020GPa[1]. According to equations (1) and (4), a_c =25.82nm and a_{cp} =155.38nm.

Obviously, the dynamic critical lapping depth of nt-CBN is much higher than that of single crystal diamond (～12nm in soft direction)[2]. It indicates that nt-CBN is not only hard but also very tough. In other words, ultra smooth surface of nt-CBN can be achieved easily by material remove at plastic region as long as the lapping depth a_p is lower than a_{cp} .

3. Experiments and results

3.1. Experimental details

Lapping experiments were carried out on a Coborn's planetary scaife bench with high dynamic balance. The lapping pressure was controlled by the weight and chunk system was used to make the nt-CBN bulk parallel with the scaife plate. During lapping process, the scaife plate was covered by a lot of diamond grains. The speed of main spindle was not higher than 2000r/min and the lapping pressure was 5N.

3.2. Lapping with coarse diamond grains

As shown in Fig 3, a small part of surface was formed by ductile material removal and most material was removed at brittle region during lapping with coarse grains. some ductile grooves can be observed in the smooth area along lapping direction. It indicates that lapped depth in the smooth area is lower than dynamic critical lapping depth. As the nt-CBN surface was not very flat, the lapped depth was larger than dynamic critical lapping depth in most of the lapped surface and thus brittle material removal resulted in very rough surface with many deep pits.

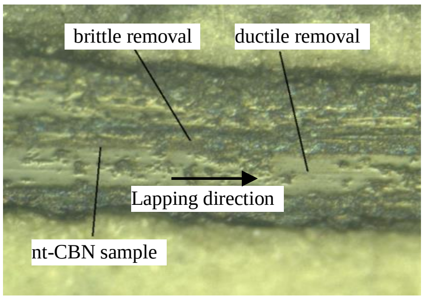

Figure 3. nt-CBN surface lapped by coarse diamond grains

3.3. Lapping with fine diamond grains

Fine diamond grains were used for lapping nt-CBN sample, where the average grain size was about 0.5μm. Considering lapping pressure of 5N, number of grains and hardness of nt-CBN, the lapped depth was theoretically lower than dynamic critical lapping depth in this lapping process.

Machined surface was measured by atomic force microscope (AFM), as shown in Figure 4. It can be observed that ultra smooth surface was formed without any pits and cracks. Besides, regular and clear ductile grooves created by abrasive grains indicates that all the material was removed at plastic region during lapping process, which proves the lapped depth was lower than dynamic critical lapping depth. Moreover, measuring results show surface roughness of lapped nt-CBN is Ra 1.83nm and Rz 2.54nm. It can be concluded that ultra smooth surface of nt-CBN can be easily achieved by using lapping process and nt-CBN possesses very good machinability.

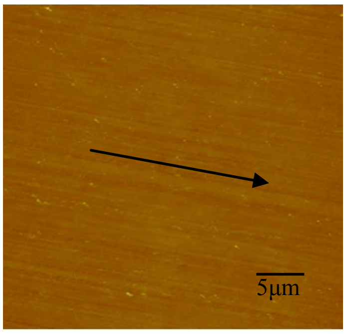

Figure 4. nt-CBN surface lapped by fine diamond grains

4. Summary

The new cutting tool material of nt-CBN with excellent physical properties is dense and free from defect. The dynamic critical lapping depth of nt-CBN is 155.38nm theoretically, which is much higher than that of single crystal diamond. According to experimental results, ultra smooth surface of nt-CBN can be easily achieved by using lapping process with fine diamond grains and nt-CBN possesses very good machinability. It is promising the nt- CBN cutting tool can be fabricated with mechanical lapping process.

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