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On the improvement of subsurface quality of CaF_2 single crystal machined by boron-doped nano-polycrystalline diamond tools

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ABSTRACT

The subsurface quality of single-crystal calcium fluoride (CaF_2) is examined by ultra-precision cutting experiments using a boron-doped nano-polycrystalline diamond (B-NPD) tool and compared with that of CaF_2 machined with a single-crystalline diamond tool (SCD). The critical depth of cut, surface morphologies, and process force did not change significantly in the plunge-cut tests. In the ultra-precision cylindrical turning tests, the surface roughness was almost the same, whereas the subsurface damage depth (SSD) changed remarkably, from ten to several hundred nanometers. The SSD depth was reduced by the use of B-NPD. Additionally, shear deformation and rotational deformation of the subsurface layer were observed. The lowering of friction coefficient at the interface between the cutting tool and the machined surface is assumed to affect the subsurface layer.

1. Introduction

Single-crystal calcium fluoride (CaF_2) is one of the important industrial minerals because of its excellent transparency, and is mainly used for optical window [1] or 157 nm lithography [2]. CaF_2 is also a candidate for whispering gallery mode micro-cavity [3]. Although CaF_2 is conventionally finished by polishing, only cutting process is required to manufacture free-form shapes, such as a cavity [4]. Thus, the surface has to be finished by cutting. Because CaF_2 is a single-crystal brittle material, its machining should be done in the ductile regime [5].

The ductile-regime cutting of brittle materials requires an extremely sharp defined cutting edge [6]. Hence, diamond tools made of natural single-crystalline diamond (SCD) or poly-crystalline diamond (PCD) are used in the ultra-precision cutting of brittle materials [7]. Particularly for SCD tool, the radius of cutting edge can be approximately 100 nm [8] or much smaller. Nevertheless, the cleavage feature and anisotropy of the mechanical properties peculiar to SCD hinder their practical applications. In contrast, PCD can avoid the anisotropic mechanical strength owing to isotropic nano-granular diamond structure; however, its mechanical properties deteriorate at high temperatures due to the metal binder [9].

Nano-binderless polycrystalline diamond (NPD) tools have been developed to overcome the disadvantages of SCD and PCD tools. Synthetically produced diamond with randomly distributed nano-sized crystalline grains can be formed into a cutting tool material by the high-pressure high-temperature method [10]. At ultra-high pressure and high temperature diamonds are synthesized by the transformation of graphite composite. Due to the randomly distributed nano-grains, the NPD tools feature better mechanical properties as compared to those of PCD and SCD tools. The grain structure imparts an isotropic material behavior, as opposed to the anisotropic behavior of the SCD-tool, since the micro-structure with transgranular boundaries prohibits crack propagation and improves fracture toughness.

Recently, electrically conductive boron-doped NPD (B-NPD) has been successfully synthesized by direct conversion sintering at ultra-high pressure and temperature using boron-doped graphite containing boron on an atomic level as the starting material. Due to its

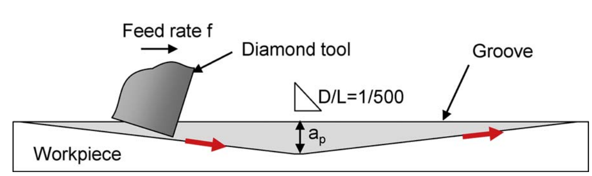

Fig. 1. Schematic of in-and-out plunge-cut test.

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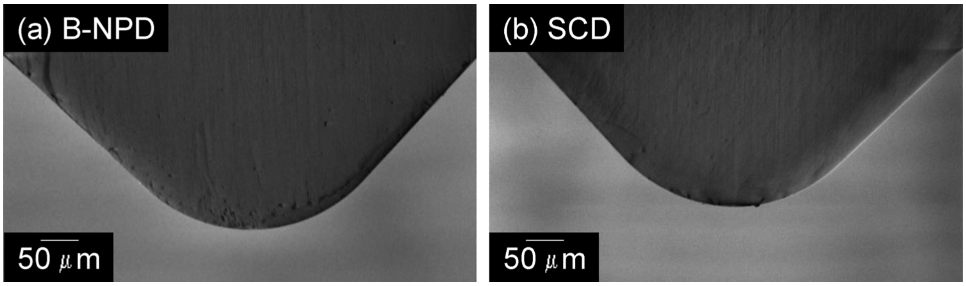

Fig. 2. SEM images of the (a) B-NPD tool and (b) undoped SCD tool.

Table 1
Experimental conditions for plunge-cut test.

Cutting parameter	Parameter value
Feed rate f [mm/min]	20
Cutting slope D/L	1/500 (0.1146°)
Axial depth of cut a_p [nm]	0–2000
Cutting plane	(100)
Cutting direction	[011]

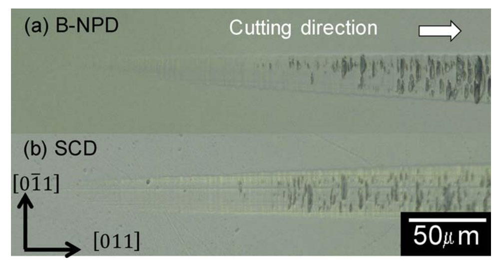

Fig. 5. Surface morphologies of the plunge-cuts of CaF_2 machined by (a) B-NPD tool and (b) SCD tool.

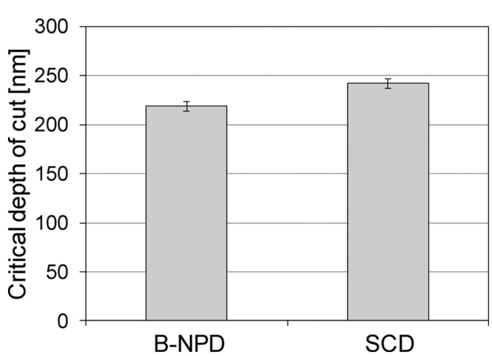

Fig. 3. Influence of tool type on the critical depth of cut (CDC).

conductivity, the B-NPD exhibit excellent wear resistance in the cutting of non-conductive ceramics [11]. Since the tribo-microplasma is avoided, the B-NPD reduces tribo-chemical wear and/or tribo-electrical wear [12].

Several experimental studies have suggested the enhancement of wear and machined surface quality by the use of boron-doped CVD diamond film coated tools for Co-cemented tungsten carbide [13–15]. However, the coated tools are prohibited for the ductile-regime machining of brittle materials due to the roundness of the cutting edge.

In this study, a B-NPD tool with a defined sharp cutting edge was manufactured, and its cutting performance in the plunge-cut tests and ultra-precision cylindrical turning (UPCT) tests was compared with that of undoped SCD tools. In previous studies, the authors have investigated that the subsurface layer was affected by variation of cutting parameters e.g. depth of cut or nose radius of the tool [16,17]. Those

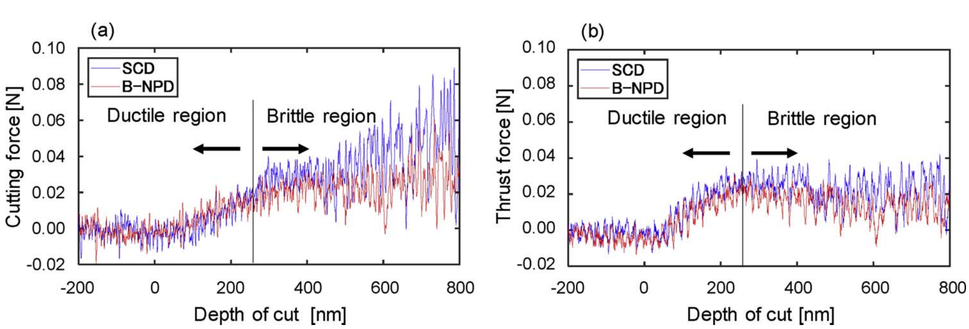

Fig. 4. (a) Cutting force and (b) thrust force as a function of estimated depth of cut.