Application of Nano-Polycrystalline Diamond to Cutting Tools

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The authors have succeeded in the production of single-phase (binderless) nano-polycrystalline diamond (NPD) by the direct conversion sintering of graphite at ultra-high pressure and temperature. NPD, consisting of diamond grains of several tens of nanometers, having fine texture, extreme hardness, and high strength without showing cleavage features and anisotropy of mechanical properties. These salient characteristics indicate that NPD has outstanding potential as industrial material suitable for cutting tools and wear-resistant tools. To evaluate the cutting performance of NPD tools, the authors conducted precision cutting tests using various work materials such as Al-Si alloy, ceramics, and cemented carbides in the respective conditions. NPD tools demonstrated significantly high cutting performance in each test compared with both conventional polycrystalline diamond tools and single-crystal diamond tools, indicating that NPD holds great promise in applications for various cutting and processing tools.

Keywords: high pressure synthesis, polycrystalline diamond, mechanical properties, cutting tool, cutting performance

1. Introduction

Diamond, said to be the hardest of all substances, has been used in a number of industrial applications because of its excellent hardness. Diamond powders have long been used as abrasive grains (grits) for polishing and grinding, with large single crystals and their sintered compacts used extensively in cutting tools, such as single-point tools, drills, and end mills, and in wear resistant tools such as dressers, styluses, nozzles, and dies. Large single crystal diamond, in particular, is used for high-precision cutting tools employed in processing precision molds for electronic parts and optical lenses, or in processing resin and plastics in high precision, supporting the basic technology in the field of precision fine processing, a domain in which Japan excels. Polycrystalline diamond, made by sintering diamond powder with binder materials, is widely used as cutting tools for use in the turning or milling of non-ferrous metals, being used in an extensive range of industries including the automotive and aircraft industries.

With workpiece materials recently becoming more difficult to cut, however, there are an increasing number of applications in which conventional single crystal diamond or polycrystalline diamond tools cannot be used. Single crystal diamond possesses the problems of cleavage chipping and uneven wear, while polycrystalline diamond exhibits limited heat resistance and machining precision. In the precision processing field, on the other hand, in which hard materials are put to a finishing process by grinding and polishing using diamond grinding wheels or abrasive grits, the precision finishing processing based on cutting, which is difficult for conventional diamond tools to handle, is increasingly needed as the trend toward higher accuracy and efficiency intensifies. This demand will further increase in the future as science, technology, and industry develop and diversify.

In order to respond to this need, new materials are required that exceed conventional diamond materials in hardness, toughness, and heat resistance. We have developed such a fantastical material—nano-polycrystalline diamond[(1)]. This is a polycrystalline diamond with a very fine structure that is obtained through direct conversion from graphite material under an ultra-high pressure, having a hardness that surpasses that of single crystal diamond. In addition, nano-polycrystalline diamond is free of cleavage and anisotropy in its mechanical properties, which are the disadvantages of single crystal diamond; in addition, it is highly heat-resistant because of the absence of binder materials. Furthermore, particles forming a crystal are as fine as several tens of nanometers, allowing high-strength, sharp cutting edges to be formed. In this way, nano-polycrystalline diamond is an ideal material for cutting tools, having a very high potential surpassing conventional diamond-based materials. We made cutting tools, as shown in **Photo 1**, of this nano-polycrystalline diamond, carrying out basic tests on precision cutting on various workpieces made of Al alloy, ceramics, and cemented carbide alloys to systematically investigate its practical characteristics[(2)-(4)]. All results of the tests show that nano-polycrystalline diamond has much more excellent cutting performances than conventional polycrystalline diamond or single crystal diamond and that the new diamond is capable of cutting high-

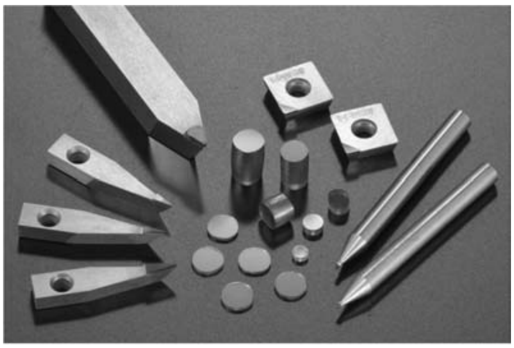


Photo 1. Nano-polycrystalline diamonds and cutting tools prepared from them

hardness materials such as binderless cemented carbide which has been very difficult to cut by conventional diamond tools. This paper reports the results of the research described above, summarizing the possibilities of nano-polycrystalline diamond being used as a cutting tool. In this paper, nano-polycrystalline diamond is referred to as NPD. In the same way, single-crystal diamond is referred to as SCD, and conventional polycrystalline diamond containing binder materials as PCD.

2. Characteristics of NPD

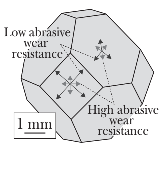
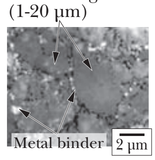
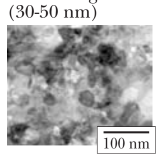
Under an ultra-high pressure of 10 GPa or more and a temperature exceeding 2,000˚C, graphite is directly converted into diamond without the use of a catalyst or a solvent. Under these conditions, polycrystalline compacts of solidly sintered single-phase diamond are synthesized by controlling the state of the starting material, pressure, and temperature conditions, and so forth. Extending this direct conversion sintering method, we synthesized nano-polycrystalline diamond (NPD) in which diamond grains with a diameter of several tens of nanometers are directly and strongly bonded to each other[(5), (6)]. Furthermore, the improvement of the starting material and synthesis chamber and the optimization of microstructure and synthesizing conditions have allowed us to establish a technology to mass-produce large and homogeneous NPD with a diameter of 8-10 mm[(1)]. The NPD that is obtained in this way has a structural texture in which very fine grains are bonded with each other with an extremely high strength, with no binder materials or heterogeneous components; for this reason, it greatly surpasses conventional diamond in terms of hardness, strength, heat resistance, and other characteristics. An overview of characteristics of NPD is given below. For more information, refer to the related literatures[(7)-(9)].

NPD has a hardness value of about 130 GPa, which is higher than that of the most common type I diamond (natural Ia type and synthetic Ib type, containing nitrogen impurities) (70-120 GPa)[(7)]. Since fine grains are very strongly bonded in NPD, plastic deformation and the development of micro cracks are hindered by the grain boundaries; this makes NPD harder than SCD. With individual grains oriented randomly, the anisotropy and cleavage that are observed in SCD do not exist and fracture toughness is high[(8)]. In addition, the hardness of NPD does not decrease significantly under high temperatures; for example, a high hardness value exceeding 100 GPa is maintained at 800˚C, exhibiting a hardness nearly twice that of SCD. While plastic deformation due to plane slip is activated by heat in SCD and accordingly hardness drops substantially, the plastic deformation prevention effect at grain boundaries, acting independently of the temperature, allows NPD to exhibit a far greater hardness value than SCD under high temperatures. In PCD, on the other hand, the effect of the binder materials (the difference in thermal expansion from diamond, in particular) causes the material quality to degrade substantially at temperatures between 500˚C and 600˚C, substantially reducing hardness. The transverse rupture strength (TRS) of NPD[(9)] is about 3 GPa at room temperature, being close to that of cemented carbide alloy and higher than that of other hard ceramic materials and PCD containing binder materials. Since NPD does not contain impurity phases in grain boundaries and has strong cohesion between grains, its TRS exhibits little decrease at high temperatures[(9)]. By contrast, the TRS of PCD decreases greatly at about 500˚C due to the effect of the binder materials as in the case of high temperature hardness. As described above, NPD is an ideal hard material that possesses high hardness, high strength, and high heat resistance at the same time.

The result of a wear test based on high-load grinding using diamond grinding wheel[(9)] shows that the wear resistance of NPD is about the same as that of SCD in the high wear resistance direction, more than 10 times that of the low wear resistance direction. Grains forming NPD are oriented randomly, with a number of high wear resistance grain surfaces appearing on the NPD surface. This significantly increases the wear resistance of NPD, with anisotropy observed with single crystals not present. In SCD, by contrast, an accumulation of cleavages accelerates wear, with remarkable wear appearing depending on the plane direction. In PCD, the binder materials cause micro cracks to occur and grains to come off, accelerating wear greatly; the amount of wear reaches 10-100 times or more of that observed in NPD depending on the grain diameter and the quantity of binder materials.

Table 1 summarizes the excellent features of NPD in comparison with those of SCD and PCD. Having high hardness and excellent wear resistance, and being free of cleavages and the orientation-dependency of hardness and wear as observed in SCD, as well as showing none of the problems of heat resistance as observed in PCD, NPD is an epoch-making hard material that is totally free of the shortcomings of conventional diamond materials.

Table 1. Characteristics of nano-polycrystalline diamond (NPD) compared with single crystal diamond (SCD) and conventional polycrystalline diamond (PCD)

	SCD	PCD	NPD
Micro structure or Image		Diamond grains (1-20 μm) 	Diamond grains (30-50 nm) 
Hardness	△ 80-120 GPa (anisotropy)	× 50 GPa	○ 110-125 GPa
Isotropy	× (anisotropy)	○	○
Fracture resistance	× (111) cleavage	○	○
Heat resistance	○ 1600˚C	× 600˚C	○ 1600˚C
Edge accuracy	○ <10 nm	× ~ 0.5 μm	○ <50 nm
Transparency	○	×	○

3. Cutting Performances of NPD

Having excellent characteristics as described above, NPD is expected to have a very high potential as a cutting tool, in particular. To verify this systematically, we fabricated various cutting tools from NPD and conducted the following cutting tests[(2)-(4)].

First, cutting processing tests were conducted on high-strength Al-Si alloy and ceramics on which diamond tools are used (3-1, 3-2). In addition, we performed ultra-hard cutting machining operations that conventional diamond tools cannot handle satisfactorily, by using a variety of workpieces in combination with a variety of processing methods including turning, milling, and planar techniques (3-3). To compare with the NPD cutting tools, we prepared PCD cutting tools from three kinds of conventional PCD containing Co binder with different grain diameters (PCD-A, -B, and -C with a grain diameter of 1 μm, 5 μm, and 30-50 μm, respectively), and SCD cutting tools from SCD of natural Ia or synthesized Ib type. We then evaluated their cutting performances under the same cutting conditions. In the following, the results of the cutting tests are described.

3-1 High-speed intermittent cutting of high-hardness Al-Si alloy

We prepared a high-precision NPD cutting tool having 0.4-mm nose radius, with a point angle of 60˚, and a clearance angle of 11˚, and cut high-strength aluminum alloy intermittently at a high speed. As workpieces, we used an A390 round bar on which four U-shaped grooves were provided to obtain intermittency, and cutting was performed under the conditions of a cutting speed V = 800 m/min, a cutting depth d = 0.2 mm, and a feed f = 0.1 mm/rev. The result of this cutting test showed that the wear resistance of an NPD tool is about the same as that of an SCD tool, 10-20 times higher than that of a conventional fine-grain-based PCD-A tool. **Figure 1** shows the cutting edges of different tools used for the 30-km-long cutting operation. In a PCD tool, wear develops mainly due to thermal degradation caused by the effect of the Co binder (occurrence of micro cracks, dropping of grains, and reverse conversion to graphite). The cutting edge of an SCD tool has a wear resistance direction of (001)<110> in major flank, showing no marked wear; at locations somewhat shifted horizontally, however, marks of uneven wear, as shown in the illustration, are observed. In contrast with these, NPD does not exhibit thermal degradation as seen in PCD or uneven wear as seen in SCD, with few wear marks seen on the cutting edge. For this reason, the surface precision of the workpiece after being machined by an NPD tool is higher than that resulting from a PCD or SCD tool.

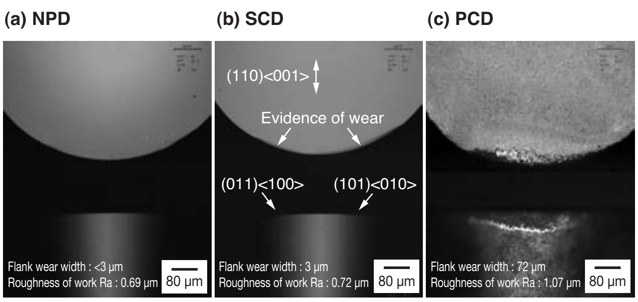


Fig. 1. Cutting edges of diamond tools after high speed interrupted cutting test of high strength Al-Si alloy (after 30 km cutting).
(a) Nano-polycrystalline diamond (NPD) tool, (b) single crystal diamond (SCD) tool, (c) conventional polycrystalline diamond (PCD) tool.

3-2 Precision cutting processing of ZnS Fresnel lenses

As an example of precision processing of ceramics, we adopted a ZnS Fresnel lens processing. Using sharp tools made of NPD and those made of SCD, with a point angle of 45˚ and a point chamfer width of 2 μm, we lathe-turned ZnS lenses with a diameter of 20 mm into Fresnel lens shapes on a precision lathe. The number of revolutions was 2,000 rpm, with a cutting depth d = 10 μm, and a feed f = 7 μm/rev. In the course of machining, the turned surface roughness of the SCD tool worsened to a value of more than 0.05 μm and the tool reached the end of its service life at the time of completion of a fifth lens, while the NPD lens exhibited surface roughness of less than 0.02 μm after the completion of the twentieth lens. **Figure 2** shows SEM photographs of the cutting edges after cutting. The SCD tool shows the shape of its cutting edge broken by the action of uneven wear (**Fig. 2 (a)**). In contrast with this, the NPD tool maintains the initial cutting edge shape even after completion of processing of the twentieth lens. With NPD having the same high resistance to wear in all directions, it is considered that the wear damage of the cutting edge shape is small and this enables the processed surface to be kept in a good condition.

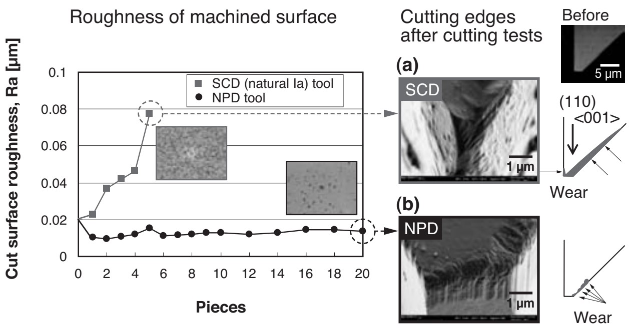


Fig. 2. Cutting performance of NPD tool in high-precision cutting of ZnS ceramic Fresnel lens.
(a) Cutting edge of single crystal diamond (SCD) tool after 2.2 Km (5pcs) cutting, (b) cutting edge of nano-polycrystalline diamond (NPD) tool after 6.3 Km (20pcs) cutting.

3-3 Cutting processing of various kinds of cemented carbide alloy

3-3-1 High feed turning of cemented carbide alloys

Following this experiment, we evaluated the cutting characteristics on various cemented carbide alloys. First, we test-fabricated an R tool of NPD (with a point angle of 90˚, R = 0.4 mm, and a clearance angle of 11˚), investigating its cutting performance on common mold-use cemented carbide alloy (D2: WC-7%Co, with a grain diameter of 2 μm).

We carried out lathe-turning-based cutting operations under high feed conditions of f = 0.1 mm/rev at a cutting speed V = 20 m/min, and with a cutting depth d = 0.05 mm. As the test result shows, the SCD tool suffered a large breakage at the initial stage (cutting distance < 20 m), while the NPD tool did not show marked breakages after the completion of 280-m cutting, exhibiting excellent wear resistance amounting to 3.5 times that of a PCD tool (5 times that of a PCD-B, and 3 times that of a PCD-C). **Figure 3** shows SEM pictures of the cutting edges of different tools used for the 280-m-long cutting operation. The cutting edge of the SCD cutting tool suffers large breakages as a result of cleavage cracking (**Fig. 3 (b)**), and the PCD cutting tool exhibits advanced wear due to the degradation of materials resulting from the dropping of grains and the catalyst action of Co (reverse conversion to graphite) and to adhesive wear (**Fig. 3 (c)**). By contrast, the NPD tool exhibits width of wear of less than 50 μm, as shown in **Fig. 3 (a)**. As this picture of the cutting edge shows, an NPD tool is worn principally by mechanical attrition, and it is considered that high wear resistance is maintained by the diamond grains with highly wear-resistant crystal planes appearing on the surface.

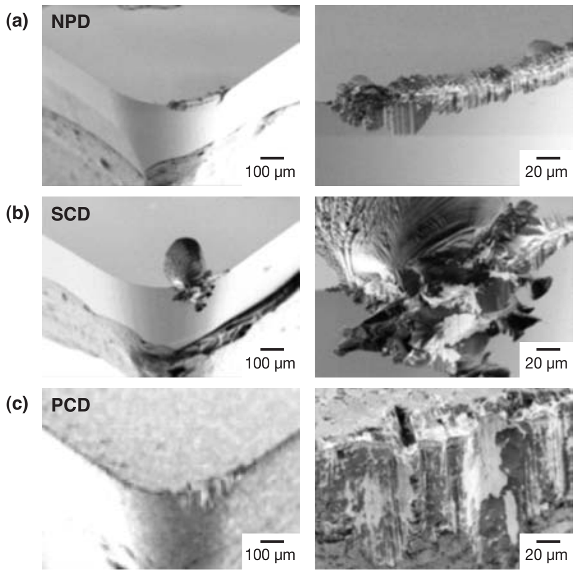


Fig. 3. Cutting edges of diamond tools after cutting test of WC-based cemented carbide (after 280 m cutting).
(a) Nano-polycrystalline diamond (NPD) tool, (b) single crystal diamond (SCD) tool, (c) conventional polycrystalline diamond (PCD) tool.

3-3-2 Precision end cutting of ultra-fine cemented carbide alloy

Next, we carried out a cutting test in which a sharp tool was used in lathe turning to confirm the potential of precision cutting machining of NPD on cemented carbide alloys. The tool used was a V-shaped tool with a point angle of 45° and a clearance angle of 10°; it was compared with SCD for evaluation. Using an ultra-high precision lathe, we conducted end lathe-turning (V = 9.6-5.2 m/min, d = 1 μm, f = 0.5 μm/rev) on an ultra-fine cemented carbide alloy (WC-12%Co, with a grain diameter of 0.3 μm). The SCD tool exhibited chipping due to cleavages at an initial stage, suffering a large breakage on the cutting edge and originating in the ridge on the cut side. By contrast, the NPD tool did not exhibit marked breakage, being capable of machining V-shaped grooves over a tool life of more than twice that of SCD tool.

3-3-3 Planer machining of binderless ultra-fine cemented carbide alloy

Using a V-shaped tool to simulate a mold for light guide panels, we conducted a planer machining test on a binderless cemented carbide alloy (WC-0%Co, with a grain diameter of 0.3 μm). The shape of the tool used was formed by a point angle of 90°, a clearance angle of 10°, and a rake angle of 20°. Using the method by which a groove is machined at V = 10 mm/min and with a feed of 0.3 μm × 4 times on an ultra-precision nano machine, we made 30 V-shaped grooves with a depth of 1.2 μm and a length of 20 mm at a pitch of 2 μm. The test showed collapse of groove shapes beginning in the first groove on the machining based on the SCD tool, while the NPD tool showed the possibility of performing V-shaped groove machining that transfers the tool shape up to about 20 grooves. **Figure 4** shows the cutting edge after the cutting of 30 V-shaped grooves. The cutting edge of the SCD tool exhibits a large breakage due to cleavage, while the NPD tool shows a breakage of only approx. 1 μm on the cutting face at the tip with the V-shape maintained.

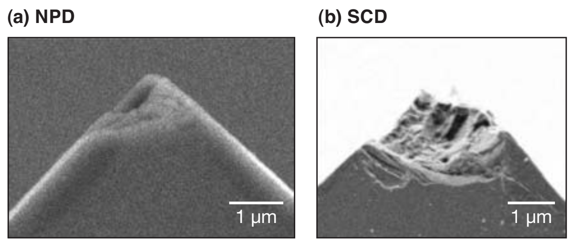


Fig. 4. Cutting edges of diamond cutting tools after high-precision grooving tests of WC-based cemented carbide.
(a) Nano-polycrystalline diamond (NPD) tool, (b) single crystal diamond (SCD) tool.

3-3-4 Fly-cutting of binderless ultra-fine cemented carbide alloy

Furthermore, we conducted V-shaped groove cutting operations based on fly-cutting on this binderless cemented carbide alloy by means of a sharp V-shaped tool (point angle of 60° and rake angle of 30°). We adopted a method by which a cut of 50 nm is made per pass and 100 passes are repeated at a cutting speed of 1,000 m/min and at a feed speed of 200 mm/min to form V-shaped grooves with a width and a depth of 5 μm each; using this method, we carried out 100 groove-machining operations. The results are shown in **Fig. 5**. The SCD tool allowed minute breakage in the cutting edge to be transferred beginning with the first groove, with marked streak-like projections and depressions appearing in the tool scanning direction and the V-shaped form having significantly collapsed by the eleventh groove. By contrast, the NPD tool allowed the twentieth groove to be machined in a V-shape. Continuing cutting operations showed that cutting a 5μm-wide groove was possible even on the 100^{th} one, though the V-shaped groove slowly became more rounded. Cutting high-hardness cemented carbide alloy using fly-cutting imposes high loading on the cutting edge—even when the cut is limited to a small size, and an SCD tool will break the workpiece easily due to cleavage. By contrast, an NPD tool that is free of cleavage characteristics excels in breaking resistance, withstanding high-loading cutting operations for a longer time.

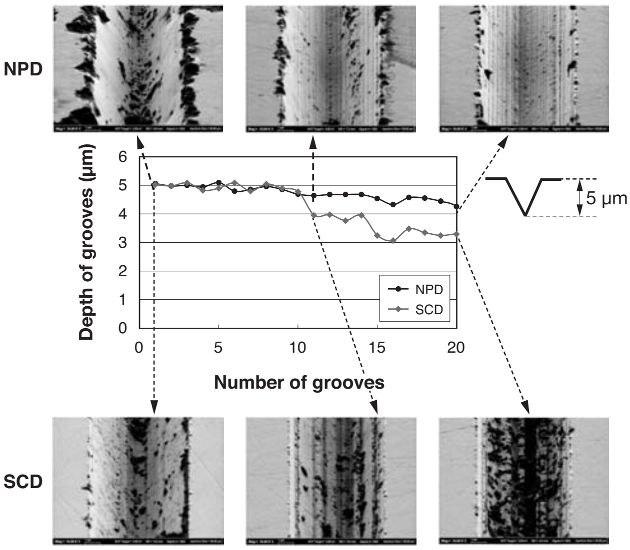


Fig. 5. Surfaces of binderless WC cemented carbide after fly cutting by nano-polycrystalline diamond (NPD) tool and single crystal diamond (SCD) tool.

3-3-5 Ball end milling of ultra-fine cemented carbide alloy

Using NPD, we test-fabricated a single-blade ball end mill (**Photo 2**) with a radius R = 0.5 mm and a clearance angle of 8° by means of laser processing and performed the milling of a mold-use fine-grain cemented carbide alloy (WC-12%Co, with a grain diameter of 0.3 μm). We first performed plane cutting of an area of about 4 × 5 mm at a spindle speed of 36,000 rpm, with a cut of 5 μm and at a feed of 1 μm, obtaining a mirror plane with Rz = 0.13 μm and Ra = 0.04 μm (one-dimensional Ra in the cutting direction is 0.018 μm) (**Fig. 6**).

We then proceeded to carry out a pattern machining test of engraving 60-μm-deep patterns, obtaining sharp patterns free of edge chipping. **Figure 7** shows, in addition to the result of the above test, results of pattern grinding in which similar shapes were engraved using an electro-deposition small-diameter grindstone for the purpose of comparison. Below **Fig. 7**, electron microscope photographs of the machined surfaces are shown. The roughness of the surface ground by means of an electro-deposition grind-

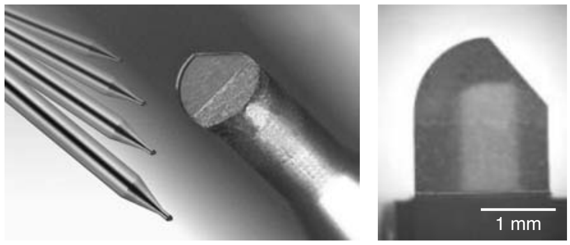


Photo 2. Ball end mill tools prepared from nano-polycrystalline diamond (NPD).

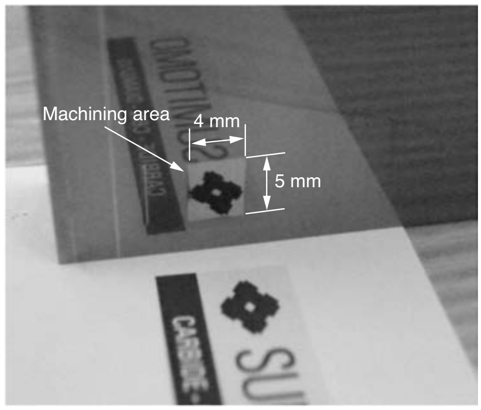


Fig. 6. Surfaces of binderless WC cemented carbide after cutting by ball end mill tool prepared from nano-polycrystalline diamond (NPD).

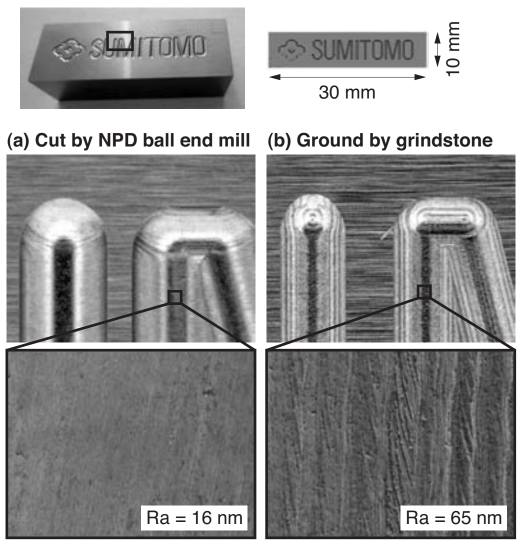


Fig. 7. Surfaces of WC-based cemented carbide after pattern machining by (a) ball end mill tool prepared from nano-polycrystalline diamond (NPD) and (b) electro-deposition small-diameter grindstone.

stone is represented by Rz = 0.46 μm and Ra = 0.065 μm, while that of the surface cut using an NPD tool was represented by Rz = 0.15 μm and Ra = 0.016 μm, a significant improvement.

4. Conclusion

NPD obtained by the graphite-to-diamond direct conversion sintering process under an ultra-high pressure of 15-16 GPa and an ultra-high temperature of 2,200-2,300°C is extremely hard, strong, and excels in wear resistance and heat resistance. As shown in **Table 1**, the individual characteristics of NPD surpass those of conventional polycrystalline diamond (PCD) and of single crystal diamond (SCD), demonstrating that NPD is very useful as a material for cutting tools. Using this NPD, we test-fabricated cutting tools, systematically evaluating their cutting performance on various workpieces when they underwent different cutting methods such as lathe-turning, planer cutting, fly-cutting, and milling. In all tests, NPD tools clearly demonstrated far better cutting performances than those of PCD or SCD tools. The reasons why NPD exhibits excellent performance are that it is free of the degradation of materials attributed to the binder materials as observed in PCD, and does not suffer large breakages due to cleavage and anisotropy in its mechanical properties as observed in SCD, and losses due to uneven wear.

NPD tools have a longer tool life in applications, such as cutting of aluminum alloys, for which conventional diamond tools are used, responding to the requirements of high-speed, high-loading machining. In addition, making the best use of the excellent NPD features of high hardness, high strength, and the absence of cleavage and anisotropy in mechanical properties will open up application fields that have been closed to conventional diamond tools, such as prolonged cutting processing (large-area processing) and precision cutting processing of ultra-hard, brittle materials, which is difficult for SCD tools to handle because of breakage and the progress of uneven wear.

As industrial products have become increasingly sophisticated, miniaturized, and integrated in recent years, upgraded and innovative processing techniques have been demanded. NPD is an epoch-making material that can adequately address this requirement. We aim to develop a range of tools that make full use of NPD, thereby contributing to the progress and development of industrial technology.

References

(1) H. Sumiya, "Novel development of high-pressure synthetic diamond ~Ultra-hard nano-polycrystalline diamond." SEI Technical Review, 74, 15-23 (2012)

(2) H. Sumiya, K. Harano, T. Sato, S. Kukino, "Mechanical properties and cutting performance of nano-polycrystalline diamond." Proceedings of 4th CIRP International conference on High Performance Cutting 2010, Vol. 2, pp. 347-350 (2010)

(3) K. Harano, T. Satoh, H. Sumiya, S. Kukino, "Cutting performance of Nano-Polycrystalline Diamond." SEI Technical Review, 77, 98-103 (2010)

(4) K. Harano, T. Satoh H. Sumiya, "Cutting performance of nano-polycrystalline diamond." Diamond Relat. Mater., 24, 78-82 (2012)

(5) T. Irifune, A. Kurio, S. Sakamoto, T. Inoue, H. Sumiya, "Ultrahard polycrystalline diamond from graphite." Nature, 421, 599-600 (2003)

(6) H. Sumiya, T. Irifune, "Synthesis of high-purity nano-polycrystalline diamond and its characterization." SEI Technical Review, 59, 52-59 (2005)

(7) H. Sumiya, T. Irifune,"Indentation hardness of nanopolycrystalline diamond prepared from graphite by direct conversion." Diamond Relat. Mater., 13, 1771-1776 (2004)

(8) H. Sumiya, T. Irifune, "Hardness and deformation microstructures of nano-polycrystalline diamonds synthesized from various carbons under high pressure and high temperature." J. Mater. Res., 22, 2345-2351 (2007)

(9) H. Sumiya, K. Harano, "Distinctive mechanical properties of nano-polycrystalline diamond synthesized by direct conversion sintering under HPHT." Diamond Relat. Mater., 24, 44-48 (2012)

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