Single-Crystal Diamond Cutting Tool for Ultra-Precision Processing

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Diamond cutting tools are used for various applications in nonferrous metal processing as they have superior sharpness and excellent wear resistance. Ultra-precision diamond cutting tools made of single-crystal diamond are used for processing resin molds for optical disk pickup lenses and smartphone camera lenses, as well as optical prism molds for liquid crystal panels. These tools are also used for the ultra-precision processing of laser reflecting mirrors in optical components. Meanwhile, a five-axe cutting machine that can operate in the 1-nm level was developed. To be employed for this machine, high-precision and small diamond cutting tools are required. This paper describes the characteristics of the ultra-precision diamond cutting tool (UPC) made of synthetic single crystal diamond named "SUMICRYSTAL." It also introduces the applications of UPC in the ultra-precision processing of the optical components that Sumitomo Electric Hardmetal Corporation produces.

Keywords: single-crystal diamond, ultra-precision diamond cutting tool, CO_2 laser, lens, mirror

1. Introduction

In response to the increasing market needs for higher precision and further downsizing of optical components and various other devices, as well as in association with the progress of ultra-precision processing technology, ultra-precision single-crystal diamond cutting tools (Photo 1) have contributed to high-accuracy microscopic processing of workpieces to an accuracy of several nanometers. A.L.M.T. Corp. began to develop an ultra-precision diamond cutting tool that would be used for the mirror-finishing of the aluminum substrates of hard disk drives (HDDs). At present, ultra-precision cutting tools are widely used to process aspheric molds and diffraction grating molds for digital video disk (DVD) pickup lenses, smartphone camera lenses, and LED illumination lenses, as well as optical prism molds for liquid crystal panels. These cutting tools are also used for ultra-precision processing of laser reflecting mirrors and various other components that play key roles in optical devices. In addition, a five-axis ultra-precision processing machine capable of cutting these optical components to an accuracy of 1 nm was developed. Ultra-precision diamond cutting tools to be used with such an ultra-precision processing machine were required to enhance its cutting accuracy. To meet this requirement, we have made efforts to develop and commercialize a new ultra-precision diamond cutting tool. In its development, we placed importance on theories and technologies in order to shift the tool manufacturing process from handcrafting as in the case of a natural diamond that is polished relying on the experience and intuition of skilled workers to an industrial process. This paper describes the performance and applications of our ultra-precision diamond cutting tools.

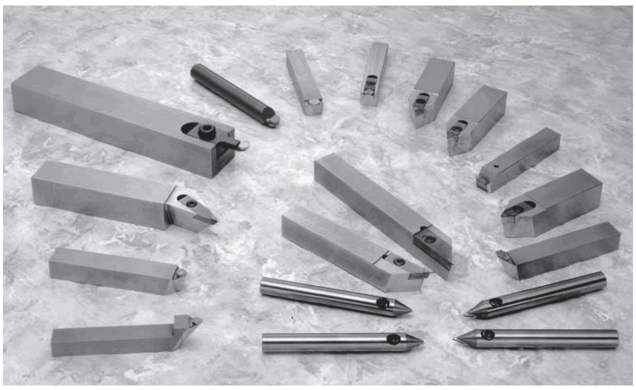


Photo 1. Ultra-precision Diamond Cutting Tools

2. Synthetic Single-Crystal Diamond "SUMICRYSTAL"

The greatest obstacle to the development of an ultra-precision diamond cutting tool as an industrial product was that the tool was traditionally made of natural diamond. Transparent, colorless, well-shaped diamonds were used for jewelry, while variously shaped rough diamonds of uneven quality shown in Photo 2 were used as cutting tool materials. Since the selection of rough diamonds and their grinding relied on the experience and intuition of the craftsmen in charge, their disparate skill levels and the variable quality of rough diamonds resulted in the non-uniform performance of cutting tools. To eliminate such disadvantages of natural diamonds, A.L.M.T. Corp. introduced SUMICRYSTAL (Photo 3), a synthetic single-crystal diamond developed by Sumitomo Electric Industries, Ltd. Although the SUMICRYSTAL was homogeneous and excellent in wear resistance, it had a shortcoming in serration grinding because, unlike natural diamonds, it did not contain partially soft portions. To overcome this disadvantage of the SUMICRYSTAL, we developed an original grinding machine that can form highly accurate, sharp cutting edges on difficult-to-cut materials without relying on the skills of craftsmen. In particular, the grinding machine utilizes the feature of the material that it always exhibits the same characteristics with respect to datum plane. The new grinding machine made it possible to grind the stable quality SUMICRYSTAL more reliably than ever and expedited the development of ultra-precision diamond cutting tools.

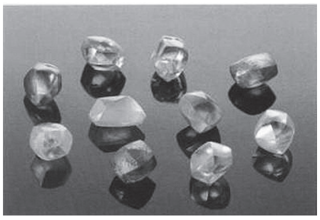


Photo 2. Natural diamonds

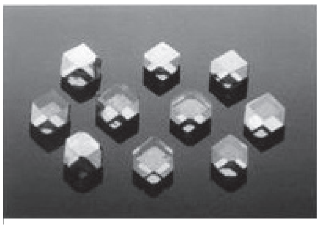


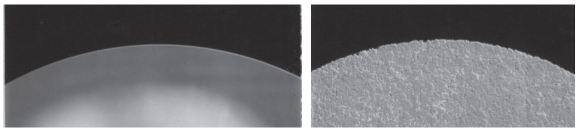
Photo 3. SUMICRYSTAL

3. Ultra-Precision Diamond Cutting Tool "UPC"

In 1985, an ultra-precision diamond cutting tool was launched on the market under the trade name of "UPC" by Osaka Diamond Industrial Co., Ltd., one of the predecessors of A.L.M.T. Corp.. At that time, the aluminum substrates of HDDs, which are storage media for computers, were mirror-finished with single-crystal diamond cutting tools. UPC was launched on the market as a tool for processing the aluminum substrates of HDDs. Although we were a late starter, the sharpness of the UPC's cutting edge compared well with those of cutting tools made by competitors. However, UPC was not widely adopted by users due to such disadvantages as a shorter service life and difficulty of initial set up. On the other hand, cutting tool users were not always satisfied with the cutting tools made by other companies, since these tools suffered variations in processed surface quality and service life. We worked to clarify the causes of the above disadvantages of UPC to improve its performance. As a result, we enhanced the accuracy of the cutting edges and optimized the crystal orientation,*1 thereby extending their service lives dramatically while reducing their variation. The know-how for enhancing the quality of cutting edges and optimizing crystal orientation was exploited effectively in the subsequent enhancement of UPC's functions/performance.

3-1 Cutting edge of UPC

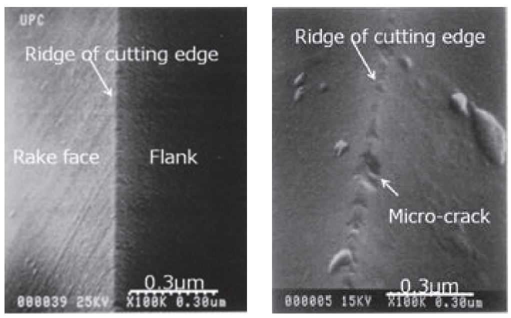
As described above, the ultra-precision diamond cutting tool UPC is made of a synthetic single-crystal diamond (SUMICRYSTAL) to eliminate the variation in quality observed in cutting tools made of natural diamond. The properties of single-crystal diamonds have been fully utilized to create remarkably sharp and durable cutting edges. Owing to such a superior quality cutting edge, UPC transfers accurately the motions of the ultra-precision cutting machine to the workpiece to perform high-precision aspheric surface processing or mirror finishing. To achieve the above purpose, the cutting edge of UPC must be shaped so accurately that it can transfer the motions of the processing machine to the workpiece without any error. In addition, the cutting edge must be so sharp and unshakable (free from microscopic irregularities, etc.) as to finish the workpiece to a uniform, smooth, flat surface. Photo 4 compares the cutting edge of UPC made of a single-crystal diamond with that of a polycrystalline diamond (PCD) cutting tool made of PCD when they are viewed from their rake faces. As this photo shows, the cutting edge of UPC, which is made of grinding a single-crystal diamond, is homogeneous and unshakable. In contrast to the cutting edge of UPC, the cutting edge of the PCD cutting tool suffers falling off of microscopic diamond particles and microscopic irregularities in the interface. Sub-micrometer size irregularities or falling off of diamond particles in a cutting edge will be transferred to the workpiece surface, making mirror-finishing of the surface impossible.



(a) UPC (b) PCD cutting tool

Photo 4. Comparison of Cutting Edges

Photo 5 compares the edge of UPC finished by our grinding machine with an edge of single crystal diamond cutting tool finished by a conventional grinding machine. As shown in (a) of the photo, the cutting edge of UPC is remarkably sharp with a roundness (sharpness) of 50 nm or less and does not include any surface irregularity. It ensures reliable cutting of slits with a width of 1 µm or less with high-accuracy surface roughness and profile. In contrast, the cutting edge



(a) UPC (b) Conventional tool

Photo 5. Comparison of Cutting Edges

finished by the conventional grinding machine includes microscopic surface irregularities that will be transferred to the workpiece surface and will degrade surface roughness.

3-2 UPC-R for processing aspherical lens mold

Demand for UPC expanded rapidly in parallel with the increase in demand for tools for processing plastic molds for aspherical plastic lenses of CD optical pickups and smartphone cameras. Immediately after CDs appeared on the world's market at the beginning of 1980, most glass optical pickup lenses were switched to plastic lenses to improve mass production efficiency and reduce production costs. Examples of UPC-R for processing aspherical lens molds, processed aspherical molds, and plastic lenses are shown in Photo 6. To meet market needs for further downsizing and higher-precision machining of optical components, the development of advanced ultra-precision lathes for lens mold processing was promoted. A newly developed lathe had the capability of controlling the cutting edge position of the tool to an accuracy of 1 nm. Cutting tools having more precisely shaped cutting edges were needed for such advanced ultra-precision processing. Aspherical plastic lenses are mass-produced by injection molding. The aspherical lens mold (electroless nickel-plated) for injection molding is profile-machined on an ultra-precision lathe by numerically controlling two-axis (X-Z) of the UPC-R, as shown in Fig. 1. If a cutting tool having a deformed circular arc cutting edge (roundness error) is used, the error will be transferred to the aspherical lens mold in the process and deteriorate its accuracy. A single-crystal diamond is very difficult to grind into a completely circular surface due to the anisotropic nature of its structure. Our grinding machine could process lens molds to an accuracy of 0.1 µm. However, the emergence of DVDs and the need for further downsized optical pickups required the cutting tool to have a cutting edge profile of 0.05 µm or less. The highest measuring accuracy of tool profile measuring devices available at that time was 0.1 µm. Therefore, we developed a proprietary profile measuring instrument and, using the instrument, succeeded in creating UPC-R having the world's highest cutting edge profile accuracy of 0.05 µm or better. Figure 2 shows an example of the data measured by the newly developed profile measuring instrument. We continuously encountered various difficulties when self-developing such a precision instrument that can measure profiles to an accuracy of several nanometers. We overcame these difficulties by implementing necessary measures after returning to basic principles. This experience helped with subsequent functional upgrading of UPC. The newly developed grinding machine and profile measuring instrument eliminated the necessity of a special skill when grinding single-crystal diamond tools into circular surfaces. This grinding was extremely difficult at that time and required a high level of skill.

Photo 6. UPC-R, Lenses, and Molds

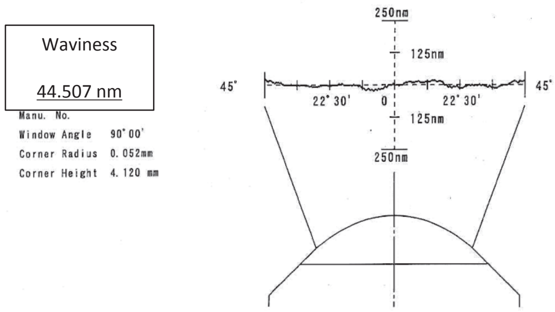


Fig. 2. Data Acquired by Newly Developed Profile Measuring Instrument

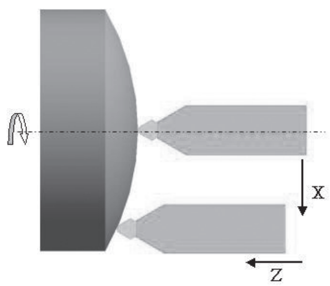


Fig. 1. Schematic Illustration of Mold Processing by Two-Axis Numerical Control

3-3 UPC for processing hologram lens

DVDs and CDs differ in signal recording position on the disk. Accordingly, they converge signal reading laser light at different points. A lens capable of focusing laser light on different points is called a bifocal hologram lens (Fig. 3). A bifocal hologram lens uses two different portions to focus laser light. One is the aspherical lens portion, while the other is diffraction gratings inscribed in the aspherical lens where laser light is condensed by using the diffraction phenomenon of light. The cutting edge of the tool for processing a hologram lens mold is required to have both a high-accuracy circular profile and a sharply pointed profile. The former is indispensable for cutting the aspherical surface of the mold, while the latter is indispensable for inscribing microscopic gratings. To meet both of the above requirements, we developed a new type of UPC shown in Photo 7 whose circular cutting edge has the world's smallest corner radius of 0.2 μm. Similar to conventional UPC-R, the extremely precisely profiled circular cutting edge of the new type of UPC transfers correctly the motions of an ultra-precision cutting machine to the workpiece, thereby cutting it into a high-accuracy aspherical surface. We also effectively used its unique grinding technology gained in the process of developing new type of UPC.

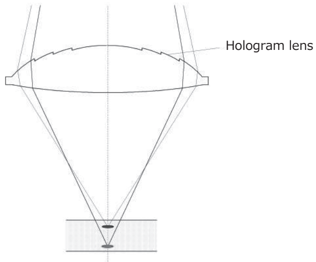


Fig. 3. Example of Hologram Lens

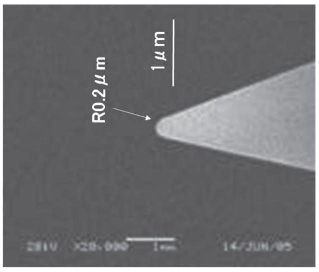


Photo 7. New Type of UPC with Cutting Edge Corner Radius of 0.2 μm

3-4 UPC-T for processing microscopically patterned mold

Light-guiding plates, optical prism sheets, and other optical components of liquid crystal panels are microscopically indented to reflect or diffuse light. The molds for forming microscopic indentations on these optical components are processed with a cutting tool having a triangle-shaped cutting edge called "UPC-T." A schematic illustration of indentation cutting with UPC-T and a photo of UPC-T's cutting edge are shown in Fig. 4. Examples of microscopically cut indentations are shown in Photo 8. Although the geometry of the cutting tool is simple, its cutting edge is superior in sharpness and the homogeneity of material that are characteristic of UPC, assuring a long service life and providing the processed optical components with superior optical properties.

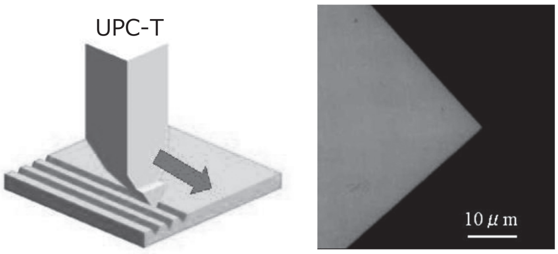


Fig. 4. Schematic Illustration of Indentation Cutting with UPC-T and Photo of UPC-T's Cutting Edge

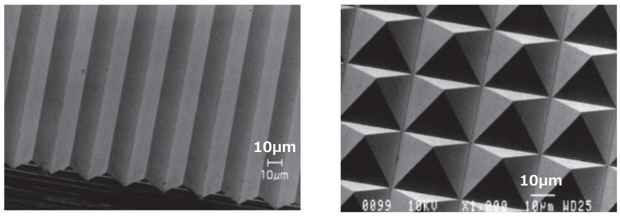


Photo 8. Examples of Microscopically Cut Indentations

4. Sumitomo Electric's Optical Components by UPC

We took part in the project for the development and commercialization of optical components for CO_2-laser systems that was launched by Sumitomo Electric. The developed components were put on the market at the beginning of 1990. Sumitomo Electric worked on the establishment of ultra-precision processing technology using an ultra-precision processing machine that processed the workpieces with the highest accuracy at that time, while we undertook the improvement of UPC so that it could meet the specifications required of the ultra-precision processing technology. As a result, the joint project team succeeded in the development and commercialization of the world's highest grade of ultra-precision optical components for CO_2-laser systems. The key to the success of the project was that the project team members grappled with the improvement of the processing machine, processing conditions, and cutting tools while solving various problems by inquiring into their root causes without sticking to the superficial aspects of cutting tool or processing method. Through this project, we saw how customers used cutting tools in practice and evolved from a mere tool maker to an enterprise that can develop and commercialize new products with the viewpoint of tool users in mind. At the same time, Sumitomo Electric strengthened the competitiveness of its products by making the most of cutting tool performance.

4-1 Parabolic mirror

A parabolic mirror used as a light condensation mirror for 5 kW or higher power CO_2 lasers is shown in Photo 9. As illustrated schematically on the right side of the photo, laser light is reflected from the mirror-finished surface and condensed at a predetermined

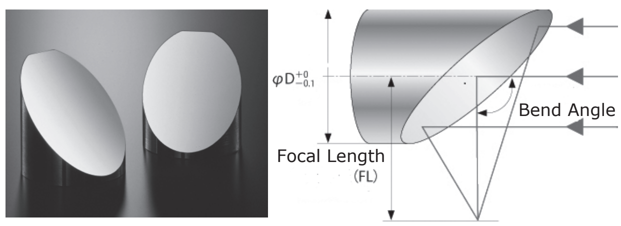


Photo 9. Parabolic Mirror and Schematic Illustration of Light Condensation Mechanism

focal point. Parabolic mirrors are made of copper that is superior in thermal conductivity and can be processed with an ultra-precision diamond cutting tool. Aluminum is used occasionally to reduce the weight of parabolic mirrors. In both cases, the reflection surfaces are coated with gold for proper reflectance in addition to superior thermal conductivity and durability. Molybdenum, having a high melting point and high hardness, is used to coat the area where a comparatively large amount of microscopic grains will accumulate when the surface is mirror-finished. UPC-R is also used to finish parabolic mirrors. When cutting a large diameter parabolic mirror intermittently, special processing expertise is required.

4-2 ZnSe aspherical lens

UPC-R is also used to process zinc-selenium (ZnSe) aspherical lenses for CO_2 laser systems (Photo 10). Aspherical lens finished by UPC-R limit the spherical aberration to a minimum, thereby realizing small light spots. ZnSe aspherical lenses display their performance when used in an optical system with short focal length and large incident beam diameter. Since ZnSe is hard to mirror-finish, optimization of the processing conditions and tool specifications is essential.

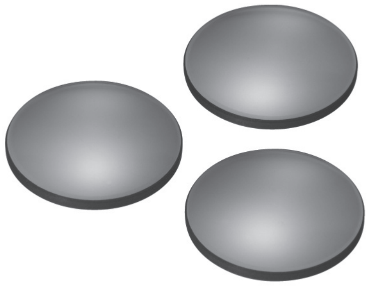


Photo 10. ZnSe Aspherical Lens

5. UPC Nano-Micro Forming Tool

At the beginning of the 2000s, a multiple-axis processing machine capable of simultaneously controlling three to five spindles to an accuracy of 1 nm was developed and used in place of a conventional lathe type ultra-precision processing machine that controlled two-axes simultaneously. Provided with an additional end-milling function, the new multi-axis processing machine made it possible to process workpieces to various three-dimensional microscopic shapes to an accuracy of several nanometers. As a tool for use in the new processing machine, we developed a new type of UPC capable of processing micrometer size workpieces to an accuracy of several nanometers and put the new UPC on the market under the trade name of "UPC Nano-micro Forming Tool."

5-1 UPC nano-ball end mill

A nano-ball end mill is used to cut three-dimensional indentations or a free curved surface on a microlens array mold for liquid crystal projector lenses, mirrors, and other optical components. An end mill with its circular cutting edge having a minimum radius of 30 μm, which is shown in Photo 11, has been developed. Similar to the circular cutting edge of the ultra-precision diamond cutting tool discussed earlier, the profile tolerance of the circular cutting edge of this mill can be reduced to 50 nm. UPC nano-ball end mill is used for three-dimensional end milling on a multi-axis ultra-precision processing machine capable of positioning workpieces to an accuracy of several nanometers. Photo 12 shows an example of a microlens array that was formed in a mold processed with UPC nano-ball end mill. This photo verifies that the axis of rotation was aligned with the center of the circular corner with a high accuracy and therefore spherical shapes were transferred correctly to the lens. In addition to this example to which only spherical shapes were transferred, any microscopic component having an arbitral three-dimensional shape can be processed by a multi-axis precision processing machine equipped with an ultra-minute ball end mill capable of transforming spherical shapes to workpieces.

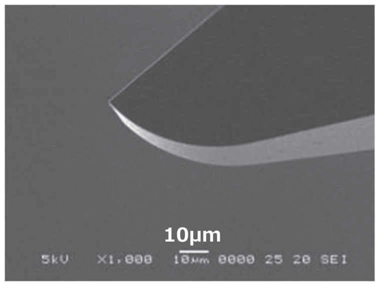


Photo 11. Cutting Edge of R30 μm Nano-Ball End Mill

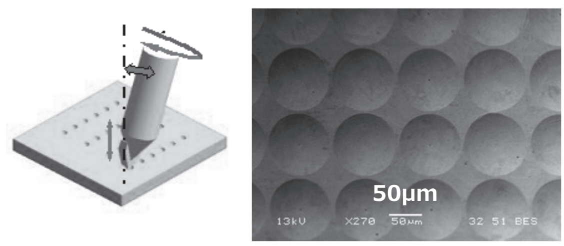


Photo 12. Example of Microlens Array and Schematic Illustration of Processing Mechanism

5-2 Nanogroove (Microscopic groove cutting tool)

A holographic optical element (HOE) consists of various complex optical systems. Comprising a number of microscopic grooves spaced at regular intervals of several micrometers, an HOE disperses or condensates light using the diffraction phenomenon of light. A typical configuration of an HOE and the schematic illustration of mold processing are shown in Fig. 5. Molds for HOEs and other optical elements of the same kind have been conventionally processed by using lithography and etching techniques both of which are known as semiconductor manufacturing techniques. However, these techniques round off the bottom edges of rectangular grooves. Deep grooves are processed in a step-by-step manner by repeating the same process several times. This method forms steps in the grooves and deteriorates the use efficiency of light. The Nanogroove cutting tool capable of cutting ultramicro grooves to an accuracy of several nanometers has solved these problems. Photo 13 shows a Nanogroove cutting tool with a 0.9 μm (900 nm) thin cutting edge that can cut the world's smallest class of grooves.

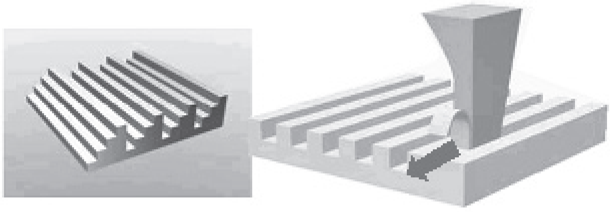


Fig. 5. Mold and Schematic Illustration of Mold Processing

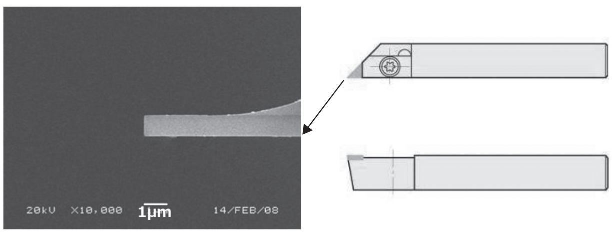


Photo 13. Nanogroove with 0.9 μm Thin Cutting Edge

Photo 14 shows 3 μm shallow grooves that were cut in an electroless nickel-plated surface by a Nanogroove with a 0.9 μm thin cutting edge. The Nanogroove made it possible to cut grooves having sharp, rectangular corners which cannot be formed by lithography that is also used for semiconductor manufacturing processes.

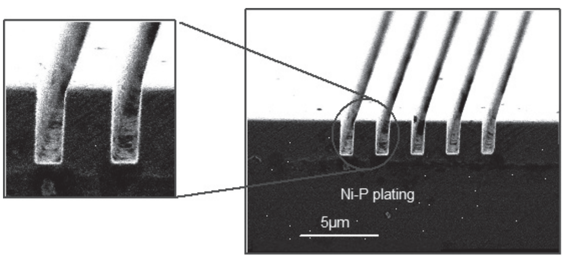


Photo 14. Example of Grooves Processed by Nanogroove with 0.9 μm Cutting Edge

6. Future Development of UPC

UPC has evolved by making the most of its advantages as a single-crystal diamond in order to meet market needs for further ultra-precision cutting. Mirror-finishing of cemented carbide and forming microscopic indentations in large surfaces are recent market needs that cannot be met by conventional UPC. To meet these needs, A.L.M.T. Corp. has been making efforts to commercialize "BL-UPC" made of SUMIDIA BINDERLESS that is a nano-polycrystalline diamond developed by Sumitomo Electric. Photo 15 shows an example of a cemented carbide mold for a small diameter glass lens that is difficult to make by grinding. Although BL-UPC is a polycrystalline diamond cutting tool, it can finish the workpiece with a surface roughness of Ra 3.5 nm that is equal to the roughness UPC, a single-crystal diamond cutting tool, can achieve when processing an electroless nickel-plated molds.

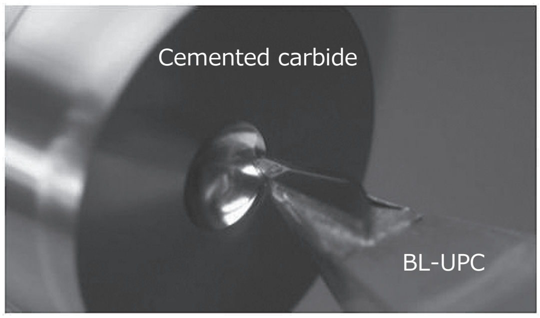


Photo 15. Processing Cemented Carbide Mold with BL-UPC

7. Conclusion

An ultra-precision cutting tool, UPC, is used to process various parts of optomechatronic products. This paper described the principal features of representative UPCs and the history of their development. To meet the needs of customers who have been devoted to the development of state-of-the-art products, we have continued to solve unprecedented problems by inquiring into their root causes and analyzed any incidentally obtained results in terms of their fundamental attributes. As a result, we succeeded in the development and commercialization of an ultra-precision diamond cutting tool, "UPC." We will continue to keep an eye on the development of nano-polycrystalline diamond and ultra-precision processing technologies, thereby maintaining its competitiveness as a leading supplier of the world's most advanced ultra-precision diamond cutting tools.

• SUMICRYSTAL and SUMIDIA are trademarks or registered trademarks of Sumitomo Electric Industries.
• UPC and BL-UPC are trademarks or registered trademarks of A.L.M.T. Corp.

Technical Term

∗1 Crystal orientation: A specific plane and direction of a crystal where atoms are arranged regularly. A single-crystal diamond is anisotropic since its hardness differs depending on plane and direction.

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