AN ULTRAPRECISION DIAMOND CUTTING TOOL WITH A 50 nm CORNER RADIUS ROUNDNESS FOR ASPHERIC TURNING

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An ultraprecision diamond cutting tool with a corner radius out-of-roundness of less than 50 nm has been developed for aspheric turning. In addition, a sharp cutting edge which can be used to continuously produce 1 nm thick chips has also been developed. Ultraprecision processing can only be achieved when all contributing factors including the machine tool, workpiece, cutting tool and working environment are optimized. The corner radius roundness profile can approximate the precision of machine tool movement through careful study of the material used for the cutting tool, enabling processing of aspheric surfaces according to theoretical values. The development of techniques for identifying microdefects in diamond and means of applying this information to tool design played an important part in these developments.

1. Introduction

Single crystal diamond cutting tools provide the highest productivity in the manufacture of mirrored surfaces, and thus are ideally suited to precision processing of components for optical uses. Now that technologies have been developed which allow control of machine tool movement to within 10 nm for ultraprecision processing of aspheric surfaces, demand has increased for diamond cutting tools that offer stable cutting performance with nanometer-order dimensional precision. This is ten times more precise than the submicron order precision conventionally considered to be the limit of diamond tools.

The ability to identify defects in diamond crystals clearly is essential to achieving such ultraprecision tools. For this purpose, the authors first developed an electron spin resonance (ESR) method of selecting uncut diamonds with fewer nitrogen-caused defects. We then developed a high resolution cathodoluminescence (CL) spectroscope with a highly efficient light collection system for the detection of weak CL emission that enables two-dimensional imaging of crystalline defects in diamond, as well as a method of using this spectroscope to observe the distribution of defects in diamond for the selection of raw diamonds.

During the development of this ultraprecision diamond cutting tool, the authors established the basis for development of a cutting tool with a sharp cutting edge enabling the generation of 1 nm thick chips, and an ultraprecision cutting tool with a corner radius roundness profile precision of 50 nm.

2. Method

When a material is bombarded with an electron beam, the electrons collide with the atoms in the material, gradually losing energy and generating electromagnetic waves through interaction with the constituent atoms of the material. CL is one kind of carrier electromagnetic wave which can be detected.

CL is the light emitted when the valence band electrons in the constituent atoms of the material are excited to a conductive band by the incident electrons, electron holes then form in the valence band, the electrons recombine and are emitted through crystal defects and impurity levels. Because the efficiency of emission changes according to the type of defect, when there is an aberration in the crystal structure, CL spectroscopy is an effective
means of analyzing aberrations in the host crystal level caused by lattice defects and other defects.

Diamonds have a large energy gap (5.5 eV), and because there are few optical sources with sufficient energy and strength to excite electrons to the conduction band, electron beams are generally used for electron excitation in diamonds. The optical properties of diamonds have therefore been investigated primarily by using CL. While many emission bands and emission centers have been reported in the visible light spectrum, strong emission is found in the blue and green bands. Band A and H3 center emissions are representative of these bands.

Band A emissions are observed in all type of diamonds. The emissions spectrum is broad, and the peak is between 2.3–3.0 eV. The mechanism of these emissions has been explained by the recombination process between donor-accepter pairs.

3. Results and Discussion

Figure 1 is a CL image of a diamond cutting tool made from a natural type 1a diamond. Crystal defects formed during the process of crystal growth can be seen. This type of diamond is not suited to ultraprecision cutting tools requiring a sharp, uniform edge.

Figure 2 is a secondary electron image of the cutting edge of an ultraprecision diamond cutting tool manufactured without giving special attention to defects in the raw diamond during the diamond selection process. The radius of curvature (ρ) of the cutting edge is about 50 nm, and there are multiple chips in the cutting edge. This is believed to be due to microdefects resulting from nitrogen or other impurities along the cutting edge. Figure 3(a) is a secondary electron image of the cutting edge after plunge cutting of 99.99% aluminum. Chips in the edge are obvious in the secondary electron image, and there are large individual differences in the cutting distance over which such

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Fig. 1. CL image of a cutting tool made with a type 1a diamond.

Fig. 2. Cutting edge of an ultraprecision diamond cutting tool (selected by convectional methods).

Fig. 3. Cutting edge after plunge cutting. (a) SE image. (b) CL image.
chip sare produced. This is commonly referred to as the "variation in tool life", and is an unavoidable result of using natural diamonds. Figure 3(b) is a CL image of this tool. The specific structure of the defects can be observed with CL in those spots conventionally considered to be chipped, and areas of weak emission indicate abnormal wear.

This finding suggests the need to investigate the distribution of crystalline defects through CL observation for the production of ultraprecision diamond cutting tools, and that the cutting edge should be located at the part of the diamond with the lowest concentration of defects.

Those sections with chipping are indicated by weak emission of bluish-purple light. These are low dislocation density areas and may be thought of as areas of abnormal wear.

Figure 4 is a secondary electron image of the cutting edge of an ultraprecision diamond cutting tool. The microphotograph (SEM) is the same as that taken in Fig. 2, but it can be seen that the cutting edge is uniform. In order to manufacture an ultraprecision diamond cutting tool of this type, a scientific method of analysis using ESR, CL or another technique is required for diamond selection, as well as ultraprecision diamond processing technologies. Since a metallic coating was applied, the photograph is not that of the actual cutting edge itself, but the radius of curvature (ρ) of the cutting edge can be inferred to be several nanometers. An ultraprecision diamond cutting tool of this type can be used to manufacture large diameter metal reflector mirrors for use in laser nuclear fusion reactors and X-ray telescopes, and in the production of memory disks for hard disk storage devices in computers, multi-faceted mirrors, and various lenses.

Figures 5 and 6 show the results of surface roughness measurements of the polishing surface formed by an ultraprecision diamond cutting tool. Figure 5 is a chart showing the results of surface roughness measurements using the diamond needle contact method. The contact needle was a knife-shaped diamond needle 0.1 μm wide and 2.5 μm long, and measurements were made with a 3 mg load. The surface roughness measured was 5 Å Rmax.

Figure 6 shows the surface roughness measured using a scanning tunneling microscope (STM) of a type IIb diamond polished in the same way as the rake face described above. In the 100 nm square area measured, a flat surface was obtained regardless of the direction of polishing.

Figure 7 is a chart showing the profile of an ultraprecision diamond cutting tool. The authors have also developed a non-contact measuring system which uses a specially designed SEM to measure the profile of the curved cutting edge of a
cutting tool at the point where cutting is actually carried out. The profile is then calculated from the measured tool profile values using the least squares method. The ultraprecision diamond cutting tool developed by the authors was shown to have a corner radius profile precision of 50 nm.

4. Conclusion

The selection of diamond crystals with ESR and CL will make a major contribution to the development of tools with an ultraprecision corner radius roundness and a sharp cutting edge.

1) In order to manufacture an ultraprecision diamond cutting tool, it is necessary to observe the microdefects in diamonds.
2) ESR enables us to select diamonds with a low defect density.
3) CL reveals the structure of diamonds, allowing the cutting point to be located in the area with the lowest defect density.
4) By avoiding areas with defects in this way, an ultraprecision cutting tool can be manufacture. More reliable cutting performance is also assured.

REFERENCES