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ORIGINAL ARTICLE

A study on the development of sub-micron single-crystal diamond tools for machining diffractive optical elements

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Abstract
Machining fine patterns of hundreds of nanometers requires the use of 5-axis equipment and fine tools with precise control. In this study, the focused ion beam process was used to manufacture diamond tools for use with ultra-precision processing equipment. In order to reduce the influence of the Gaussian distribution of the beam during FIB milling machining, a lift-off process was performed. After coating the surface of the diamond with Pt up to 2.47 µm, FIB milling was carried out. In order to manufacture ultra-precision diamond tools, single-crystal diamond (SCD) was used as the tool tip and cemented carbide was used as the insert. A process study was conducted on the process of focused ion beam machining by applying the vector scan (rectangle type) and raster scan (cleaning type) methods in combination. As a result of conducting experiments according to each machining condition, a tool with a cutting-edge width of 486.76 nm was produced. We performed machining tests on Ni-plated material using a prepared tool with a 500 nm ultra-precision diamond tool.

Keywords Focused ion beam (FIB) · Ultra-precision · Diamond tool · Side clearance angle · Fabrication · Diffractive optical element (DOE)

1 Introduction

Recently, each industry was paying attention to the head-up display technology in which various technologies are converged to implement augmented reality (AR) and virtual reality (VR) technologies in the 4th industrial revolution. Researchers have studied nano-scale technology to store various information in a single microstructure to enhance technological prowess to increase technological precision in semiconductor technology and aerospace, which have high technological barriers worldwide [1]. Optical systems used in 3D displays and aerospace fields are designed very precisely with complex microstructure patterns.

In the exposure method used in semiconductor processing technology, an optic pattern can be removed by design a pattern with a size of several micrometers on an optical lens. However, there are technical limitations in processing micropatterns on optical lenses by non-contact processing. Due to the Gaussian beam distribution generated from the laser beam, it is difficult to process it into a precise structure. Ultra-precision optical lenses and F-theta lenses have free-curved surfaces and have nanostructures because they are designed in fine pattern structures [2]. When a pattern was processed by the photolithography method used in the semiconductor process, since the shape of the beam is a Gaussian shape, it is very difficult to implement shape precision and surface precision because round edges occur due to the influence of the beam. Since it is very difficult to precisely process a fine pattern on a diffractive optical element using a non-contact processing method, there is a method of directly processing a pattern on a material using an ultra-precision cutting tool. However, in order to implement ultra-precision cutting, high-precision 5-axis machine tools and ultra-precision tools are required, and complex measurement techniques are required to measure free-form surfaces [3].

The element design technology of ultra-precision machine tools requires a lot of consideration because the

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entry barrier is high. C. H. Park analyzed the structural resonant frequency and displacement through the finite element method (FEM) model to evaluate the design and fabrication of a cylindrical roll forming machine for processing micropatterns on large samples (0.6 m × 2.5 m) [4, 5]. WS Fong used a focused ion beam to analyze the removal rate and surface condition due to ion sputtering. He also proposed a micro-pillar processing technique by processing Al6061 material with a tool made using a single-crystal diamond tool [6]. MB Ritchey conducted an experiment to fabricate a two-tip microtool by applying the sputtering technique of a focused ion beam for ultra-precision machining [7]. P.R. Munroe performed processing analysis through diamond cross-sections using a Ga + ion source and a focused ion beam on diamond [8].

Researchers proposed process technology for ultra-precision processing technology and tool development. However, it was difficult to secure a high aspect ratio capable of processing micropatterns on a diffractive optical element (DOE) and analyzing the optical characteristics of the diffractive optical element. S. Y. Baek proposed research on the FIB (focused ion beam) process, which coats diamond with nanoscale thickness of chromium and nickel, to develop ultra-precision diamond tools. In addition, to reduce the effect of the Gaussian beam distribution on the focused ion beam process study, the lift-off process was used to reduce the effect of the beam [9–12]. Beam current and tilting angle were varied to fabricate ultra-precision diamond tools, and analyses were performed according to the conditions during the processing of the focused ion beam [11]. W.J. Zong conducted research on the design and manufacture of diamond cutting tools, explained diamond crystals, and studied design [13].

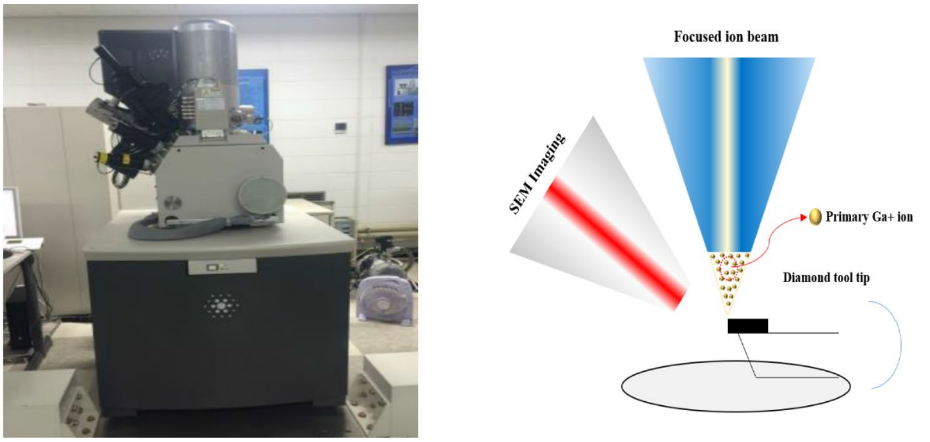
This paper proposes the development of ultra-precision diamond tools required of the ultra-precision 5-axis processing equipment for machining diffractive optical elements (DOE) with contact machining method. Instead of manufacturing tools using a grinding method, tools were developed through focused ion beam machining technology and lift-off technology. In addition, in consideration of the size of the micropattern to process the diffractive optical element, the development of a single-crystal ultra-precision diamond tool with a cutting-edge width of 500 nm was proposed.

2 Process study considering side clearance angle

2.1 Experiment method

An ultra-precision machine was used to manufacture submicron single-crystal diamond (SCD) cutting tools. Experiments were conducted using the FIB (FEI Company, System Nova 600) to develop nano SCD tools, as illustrated in Fig. 1. Figure 1 (a) displays a photograph of the equipment used in the experiment, and Fig. 1 (b) shows a schematic diagram of machining an ultra-precision diamond tool using a Ga + source in a focused ion beam. FIB milling machining technology combines precision technology, including scanning electron microscopy (SEM), and can employ nanoscale machining technology.

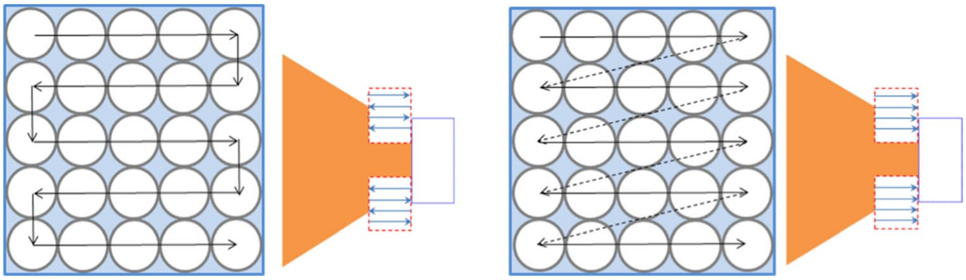
To manufacture an ultra-precision diamond tool, a platinum (Pt) coating was applied to the surface of the diamond tool, followed by applying the principles of vector scan (rectangle type) and raster scan (cleaning type) to examine various machining conditions due to the cutting-edge width. The platinum coating was deposited on the diamond surface up to 2.47 μm. The vector scan (rectangle type) method, which increases the current of the focused ion beam while considering the machining time, produces low surface roughness but can shorten the machining time and reduce the roughness of the cutting edge. On the other hand, a raster scan



(a) focused ion beam equipment

(b) tool fabrication method of sub-micron

Fig. 1 Photograph of **a** focused ion beam system (FEI, NOVA600 Nanolab) and **b** fabrication process of sub-micron tools using Ga + ion in a FIB milling



(a) vector scan (rectangle type) **(b) raster scan (cleaning type)**

Fig. 2 Schematic image of the scanning method on focused ion beam: **a** vector scan and **b** raster scan

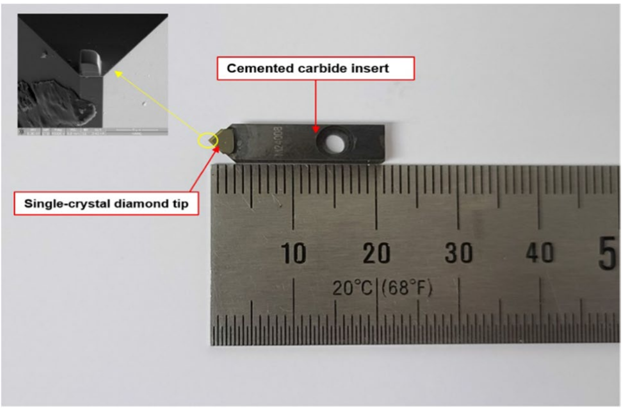


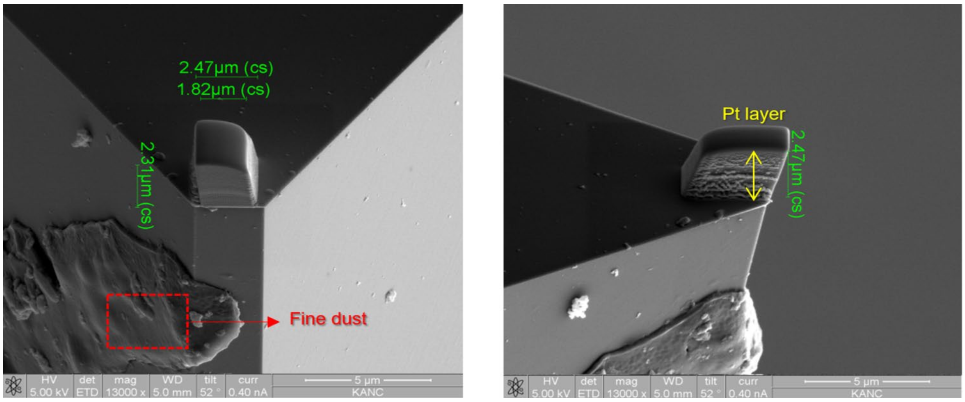
Fig. 3 SEM images of single-crystal diamond tool before FIB milling and sample top view of cemented carbide insert

(cleaning type) enables more precise diamond cutting edge machining. Therefore, in this study, the process of vector scan and raster scan was applied simultaneously, as shown in Fig. 2, to design the fabrication method for ultra-precision diamond tools with the aim of improving economic efficiency.

In this paper, SCD was used as the material for the insert used in the experiment to manufacture the tool. The specimen size for the diamond tool is shown in Fig. 3. In addition, in order to measure the tool in the rectangle type, the tool tip was measured using a microscope in the FIB equipment. The edge of the tool becomes round due to the Gaussian beam profile caused by beam emission during FIB machining. To reduce the Gaussian beam effect, Pt coating is applied to the surface of the diamond tool by applying the lift-off process used in the semiconductor process. Figure 4 (a) shows an image of a sample with a Pt coating thickness of 2.47 μm on a diamond tool. Through Pt coating, the straightness of the FIB beam was increased to prevent rounding of the blade end of the tool. Figure 4 (b) shows the side view of the diamond tool, and the stacking height of Pt is 2.47 μm.

2.2 Fabrication of ultra-precision diamond tools

To improve the roundness and sharpness of diamond tools, processing conditions were stepwise selected to manufacture ultra-precision diamond tools, as shown in Table 1. The table was rotated under the selected processing conditions to produce a sharp tool for the manufacture of a trapezoid-shaped tool. The reason for making the tool in a trapezoidal shape is that the machined area is the same when the tool is made square in shape. Beam current conditions were fixed at 7 nA on the prepared specimen, and a random machining time was given until the shape of the cutting tool appeared, so that the cutting tool edge would become rectangular.



(a) front view of the sample **(b) side view of the samples**

Fig. 4 SEM images of single-crystal diamond tool before experiment (2.47 um Pt coating layer): **a** front view of the sample and **b** side view of the sample

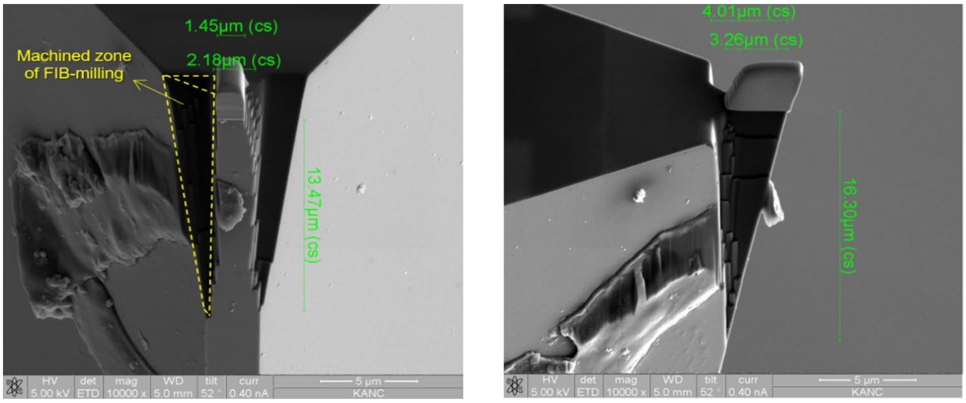
Table 1 Machining conditions of focused ion beam for ultra-precision diamond tool fabrication

No	Type	Tilting angle (°)	Beam current (nA)	Rotating (°)
1	Rectangle	4	7	-
2	Cleaning	0	1	-
3	Cleaning	1.5	0.1	0.2
4	Cleaning	1.5	0.1	0.2
5	Cleaning	1.5	0.1	0.2

Figure 5 (a) confirms a cutting-edge width of 2.18 µm. Figure 5 (b) confirms that the rectangular shape is maintained precisely when the side part of the specimen is processed and measured.

In the second machining process, the conditions of tilting angle 0° and beam current 1nA were fixed for a raster scan (cleaning type). A random machining time was given until the cutting tool shape was achieved. It was found that a more precise shape and cutting surface were obtained compared to using 7 nA, and the Pt coating maintained the shape of the cutting tool precisely. The results of the experiment under condition 2 are shown in Fig. 6. Figure 6 (a) shows that the cutting width is 1.01 um, which is smaller than the rectangle method. The surface of the tool was improved in the cleaning type process, and sharp machining was carried out. The machining conditions for steps 3–5 of the cleaning type were selected identically, with a tilting angle of 1.5°, beam current of 0.1 nA, and rotating angle of 0.2°. The side surface of the cutting tool was precisely machined by performing 4-step processing with the same conditions to manufacture a finer cutting tool after securing the cutting tool shape as a result of the 3-step processing. Figure 7 shows that the cutting edge gradually decreased to a nano-scale width. The rotating angle of 0.2° was given in the focused ion beam machining to consider the side clearance of the tool.

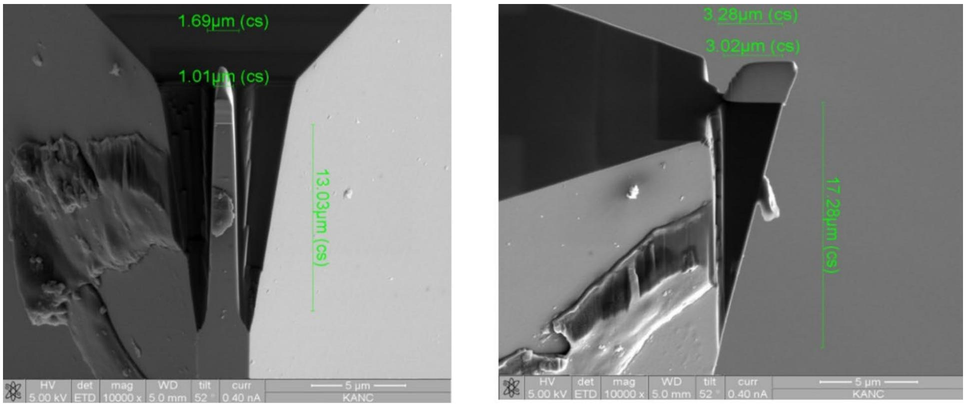
The experiment is the result of the focused ion beam using the fourth machining condition in Fig. 8. The cutting-edge width is analyzed to be 649 nm, as can be seen in Fig. 8 (a). Also, it was found that rounds were formed in the Pt layer as machining proceeded due to the influence of the Gaussian distribution of the beam. The length of the processed diamond tool is 2.93 um, as show in Fig. 8 (b) and



(a) front view of the sample

(b) side view of the samples

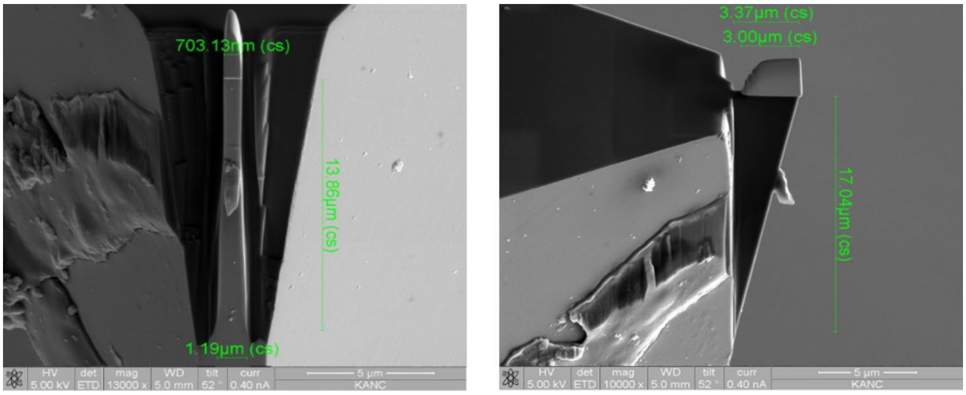
Fig. 5 SEM images of single-crystal diamond tool by focused ion beam machining experiment of step 1 rectangle type: **a** front view of the sample and **b** side view of the sample (tilt angle: 52 ± 4°, beam current: 7 nA, and voltage: 30 kV)



(a) front view of the sample

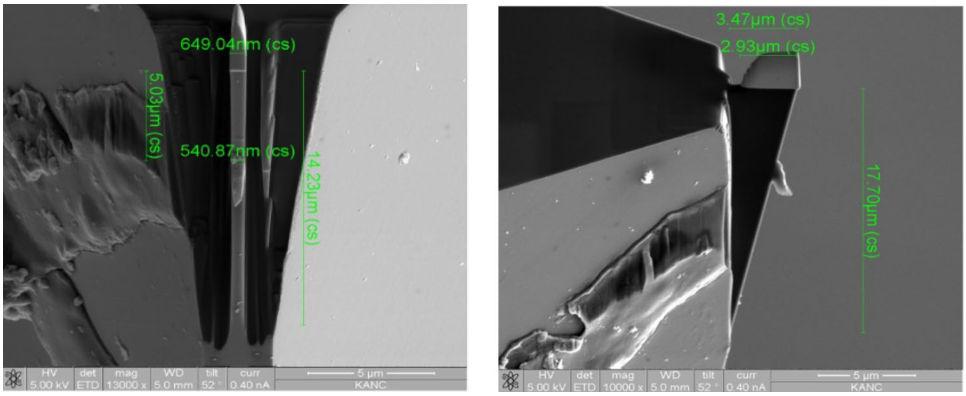
(b) side view of the samples

Fig. 6 SEM images of the single-crystal diamond tool by focused ion beam machining experiment of step 2 cleaning type: **a** front view of the sample and **b** side view of the sample (tilt angle: 52 ± 0°, beam current: 1 nA, and voltage: 30 kV)



(a) front view of the sample **(b) side view of the samples**

Fig. 7 SEM images of the single-crystal diamond tool by focused ion beam machining experiment of step 3 cleaning type: **a** front view of the sample and **b** side view of the sample (tilt angle: 52 ± 1.5°, beam current: 0.1 nA, rotating: 0.2°, and voltage: 30 kV)



(a) front view of the sample **(b) side view of the samples**

Fig. 8 SEM images of the single-crystal diamond tool by focused ion beam machining experiment of step 4 cleaning type: **a** front view of the sample and **b** side view of the sample (tilt angle: 52 ± 1.5°, beam current: 0.1 nA, rotating: 0.2°, and voltage: 30 kV)

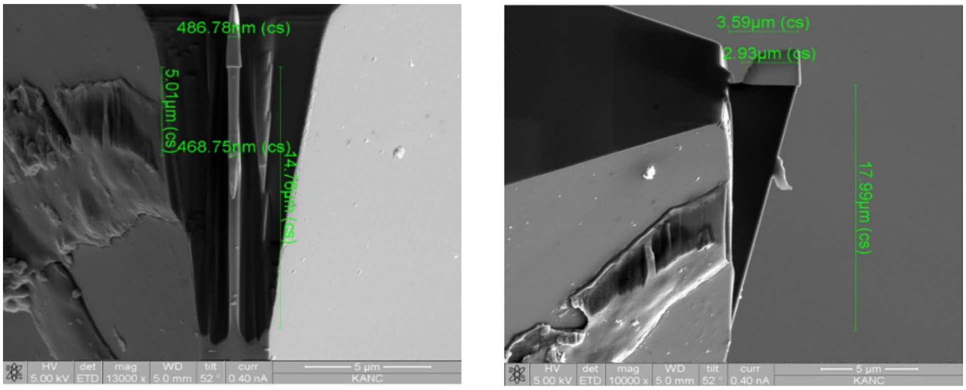
the cutting edge width is in nanounits. Also, if the length of the tool is long, there is a risk of damage. In this study, the cleaning type, tilting angle 1.5°, Beam current 50 pA, and Rotating 0.2° were selected identically in 5 Step, the final machining condition, and through the final processing, ultra-precision diamond tools with cutting edge width of 500 nm less were manufactured as show Fig. 9. The length of the tool processed through focused ion beam machining was 2.93 um, and a tool with side clearance was manufactured. In addition, since it is a nanoscale diamond tool, care should be taken as it may cause breakage in the process of separating the insert after FIB milling.

3 Ultra-precision machining using sub-micron tool

In this chapter, we aim to investigate cutting experiments using precision diamond tools that have been developed. In order to perform precision cutting, the Toshiba ULG-100C(H3) 3-axis turning machine shown in Fig. 10 (a) is used. Additionally, to perform cutting experiments on nickel-plated materials using diamond tools, nickel-coated samples were prepared, as shown in Fig. 10 (b).

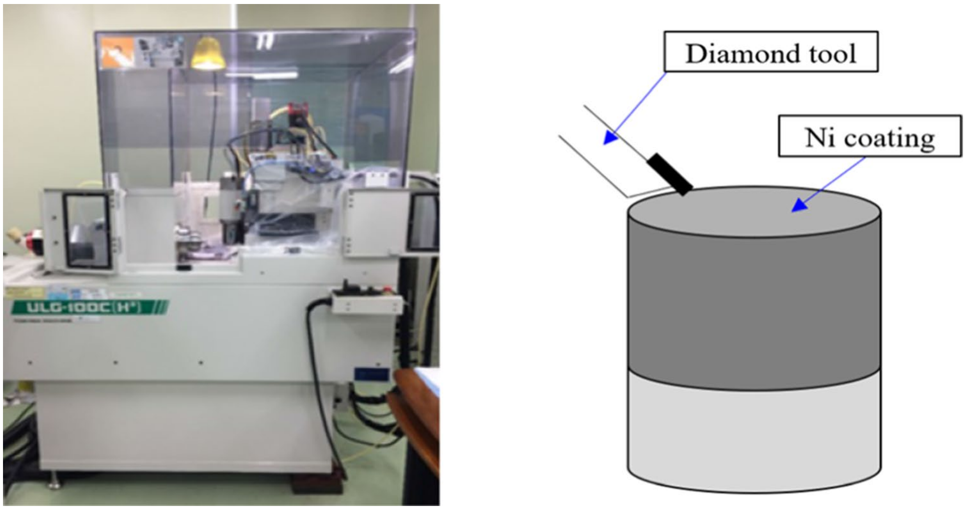
As shown in Table 2, five main cutting parameters were selected for the cutting process, and a pitch size of 1 μm was chosen for sub-micrometer pattern processing. In addition, patterns were processed with a 1-μm gap in precision cutting experiments. In micro-precision cutting, zero-point setting is crucial in pattern processing. Furthermore, due to the difficulty of monitoring phenomena that occur during processing in real-time, errors in zero-point setting can lead to positioning errors between the tool and the sample, causing diamond tools to break down.

We have conducted machining tests on nickel-plated material using a 500-nm ultra-precision diamond tool. The machining was performed in both the forward and reverse directions to observe the difference in the machining patterns. Figure 11 shows the machining pattern generated when machining was performed in the forward direction. A pitch size of 1.04 μm was observed in the pattern, and the material's cutting depth was confirmed to be 298.22 nm, as



(a) front view of the sample **(b) side view of the samples**

Fig. 9 SEM images of the single-crystal diamond tool by focused ion beam machining experiment of step 5 cleaning type: **a** front view of the sample and **b** side view of the sample (tilt angle: 52 ± 1.5°, beam current: 0.1 nA, rotating: 0.2°, and voltage: 30 kV)



(a) Machining equipment (b) Ni coating sample

Fig. 10 Photograph of preparation of experiments to process ultra-precision fine patterns: **a** machining equipment and **b** Ni coating sample

Table 2 Machining conditions of focused ion beam for ultra-precision diamond tool fabrication

Parameters	Value	
	Forward machining	Reverse machining
Feed rate (mm/min)	0.005	0.005
Cutting depth	300	700
RPM	1000	1000
Pitch number	200	100
Pitch size	1	1

the tool precisely contacted the material. While the copper-plated material showed a lot of burrs and unclear pattern shapes, the nickel-plated material exhibited clear patterns [14].

The results of machining in the reverse direction are shown in Fig. 12. While the cutting depth was accurately achieved when machining in the forward direction, a significant difference was observed in the cutting depth, which was measured to be 114.21 nm, when machining in the reverse direction. It is analyzed that this discrepancy was due to the material being compressed during machining in the reverse direction, causing inaccurate machining by the tool.

4 Conclusion

In this study, an ultra-precision diamond tool was manufactured in a rectangular shape, taking into consideration the size of the pen to process a diffractive optical element with

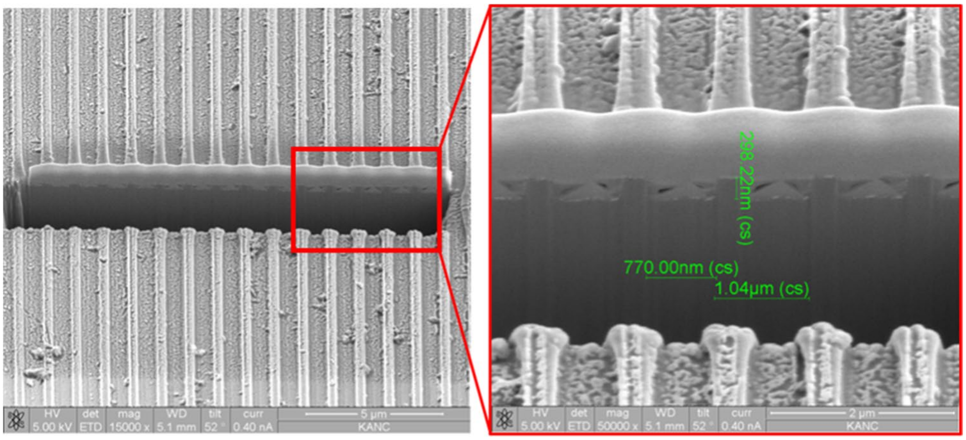


Fig. 11 Analysis result of ultra-precision fine pattern through forward rotation machining

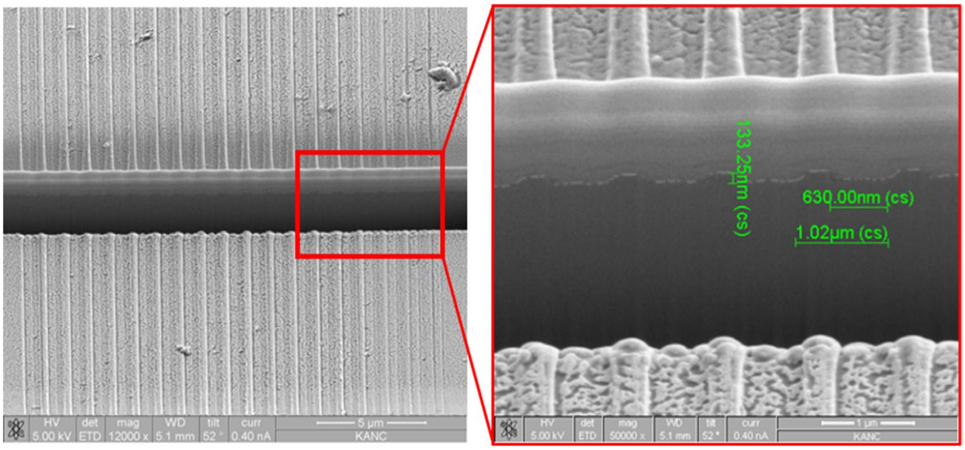


Fig. 12 Fine pattern analysis result of Ni corning material through reverse machining

a complex structure and micropattern shape. Single-crystal diamond was used to develop the tool, and the FEI Nova 600 NanoLab equipment was used to process it, with the tool material processed using Ga + ions. Additionally, 2.47 µm of Pt was laminated on the diamond tool sample using the lift-off process, which is commonly used in semiconductor processing, to reduce the influence of the Gaussian beam distribution generated in focused ion beam processing.

The machining conditions for laminating Pt on the diamond material and processing the ultra-precision diamond were carried out by fixing the acceleration voltage of the ion beam to $V = 30$ kV and changing the current and rotating conditions. The angle of rotation was used in the cleaning process considering the side angle of the tool. The scanning method of the focused ion beam was applied by combining vector scan and raster scan methods. In the cleaning process, the cutting-edge width of the tool decreased as the surface improved after machining.

Under machining conditions 3 and 4, using the cleaning process, tilting angle of 1.5°, and beam current of 0.1 nA, the tool was rotated 0.2° to secure the cutting tool shape. The same conditions were used to manufacture a more precise cutting tool under machining condition 4; as a result, the side surface of the diamond tool was precisely machined. It was confirmed that the cutting-edge width of the cutting tool gradually decreased. The effect on sharpness was confirmed by the beam current and rotating conditions. Using 5 machining conditions, the cutting-edge width was 486.76 nm, and the tool length was 2.93 µm on the side.

A machining experiment was performed using a 500-nm ultra-precision diamond tool, and the results were compared by machining the material in both forward and reverse directions. In the forward direction, the occurrence of a clear machining pattern was confirmed through the appearance of the material and the cutting section. However, when the material was machined in the reverse direction, an unclear pattern was observed and the machining was not successful.

Author contribution Seok-Jae Ha and Sung-Taek Jung conceived and designed the study, and all authors contributed to data analysis and writing. All authors discussed the results and commented on the manuscript.

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Declarations

Competing interests The authors declare no competing interests.

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