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Development of a manual multi-axes workpiece adjustment system for ultra-precision diamond machining

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Abstract
This paper describes the development and performance evaluation of a manual multi-axes workpiece adjustment system for ultra-precision diamond machining that is capable of holding a CaF_2 specimen with high positioning accuracy without pre-machining. Experiments revealed that the specimen alignment system developed in this study has sub-micrometer adjustment resolution and demonstrates a stiffness that can withstand diamond cutting forces. Applying this system to diamond cutting of CaF_2 produced an error of nominal cut thickness of at most 10 nm on both ends of the 10.5 mm cutting length and achieved a defect-free finished surface.
single crystal calciumfluoride, CaF_2, multi-axes work piece adjustment system, specimen alignment, ultra-precision machining

1. Introduction

Single crystal calcium fluoride (CaF_2) has an exceptional transmission performance that makes it ideal for transmissive optics in the ultraviolet and vacuum ultraviolet wavelength range. Generally, products exploiting CaF_2 are manufactured through finishing processes such as micro-grinding and polishing after cutting and grinding. Currently, such products demand miniaturization, and the application of these conventional manufacturing processes may not be able to achieve the required accuracy. In this regard, ultra-precision machining of CaF_2 using a diamond tool as a solution has been attracting attention. However, given that CaF_2 is a brittle material with high anisotropy, diamond cutting may damage the surface and subsurface of CaF_2, which could deteriorate its optical performance. To date, there have been no reports that define the relation between the subsurface damage and the optical performance of diamond-turned CaF_2.

Generally, ultra-precision machining requires pre-machining of a specimen to maintain the positioning accuracy after being attached to a machine tool axis. However, as damage induced by pre-machining needs to be avoided, precisely aligning the specimen to the machine tool axes without pre-machining is imperative. In this research, a manual multiaxial workpiece adjustment system was developed and evaluated. CaF_2 specimens were analyzed through cutting experiments to verify the applicability of the alignment system to ultra-precision diamond cutting of CaF_2.

2. Design and fabrication

The specimen alignment system necessitates high adjustment resolution and sufficient stiffness to withstand the force of diamond cutting. In this study, a kinematic mount was selected, originally developed for optical components adjustment. Fig. 1 shows a 3D model of the designed alignment system (left) and its schematic diagram (right). The kinematic mount was fixed to the aluminum plate using a jig, and the aluminum plate was attached to the main spindle of the ultra-precision machine. To fix the CaF_2 material by vacuum, the hole in the center of the aluminum block was connected to the main spindle of the vacuum supply through the kinematic mount, hose and the groove of the aluminum plate.

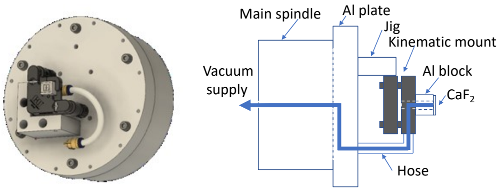

Figure 1 3D model and schematic of the specimen alignment system

3. Investigation of positioning accuracy and stiffness

3.1. Positioning accuracy of specimen alignment system

After the CaF_2 specimen was attached to the kinematic mount, the positioning accuracy of the alignment system was determined. As shown in Fig. 2, when the adjusting screw of the kinematic mount was rotated, displacement was different on both sides of the specimen. Displacement in this experiment is defined as the difference between the "high" and "low" positions of the specimen, and it was measured by using a chromatic displacement confocal distance measuring technique. Measurement values showed that when the adjustment screw was turned by 10°, displacement of approximately 1.7 µm was

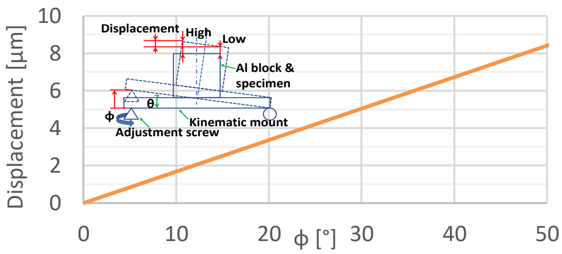

Figure 2 Displacement definition; Relationship between displacement and rotation angle of adjustment screw (ϕ)

observed. From this, it was clarified that the system is capable of positioning accuracy of a micrometer or a sub-micrometer, such that the specimen alignment system was eventually attached to the main spindle of the ultra-precision machine, and the positioning experiment of the CaF_2 specimen was carried out. In the process, a 10.5 mm square specimen was attached using a vacuum supply connected to the main spindle of the machine. As shown in Fig. 3, after installing the displacement meter on the upper left of the specimen, displacement was measured by moving the machine axis by 9 mm in both the horizontal and vertical directions respectively, and the inclination of the sample was adjusted by using an adjustment screw. This process was repeated several times for each direction, which resulted in setting the sample at minimal installation errors of 40 nm and 80nm in the horizontal and vertical directions, respectively.

Figure 3 Verification experiment of positioning accuracy

3.2. Stiffness of specimen alignment system

The stiffness of the specimen alignment system was assessed by investigating the displacement of the mount when a cutting force was applied to the workpiece. The force corresponding to the cutting force was determined byfixing a weight to the mount. According to Wang et al. [1] on diamond cutting of CaF_2, the cutting force was approximately 0.8 N at the maximum. From this, the maximum load was set to 2 N and displacement was measured while increasing the load by 10 g up to 200 g. Measurements were repeated five times for each condition. Since the kinematic mount consists of three constraining surfaces of cone, groove, and plane as shown in Fig. 4, stiffness was assumed to differ in each direction. For this reason, the displacement in each direction was measured while rotating the kinematic mount after every 90°. Fig. 5 shows the relationship between the measured force and displacement. Displacement increased as force increased and was smaller in the vertical direction (upward and downward) than in the horizontal direction (left and right), due to the force acting parallel to the groove in the horizontal direction, as shown in Fig. 4. The force was applied in the vertical direction of the groove, such that the displacement in the vertical direction was small. Moreover, the downward direction had the highest stiffness, and the displacement was 80 nm at 1 N and 156 nm at 2 N under the same condition. These experimental results of positioning accuracy and stiffness confirmed that the specimen alignment system used in this study can be applied to ultra-precision diamond cutting of CaF_2.

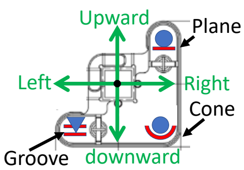

Figure 4 Structure of kinematic mount and definition of orientation

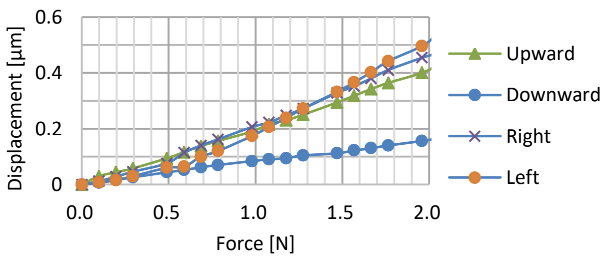

Figure 5 Relationship between force and average displacement

4. Cutting experiment of CaF_2

Cutting experiments were conducted to verify the applicability of the sample alignment system to diamond cutting of CaF_2 specimen provided by Carl Zeiss Jena GmbH Germany. As shown in Fig. 6, linear planar cutting was performed using a diamond tool which had a rake angle of 0 ° and nose radius of 1 mm. The cutting direction was set to the <10$\bar{1}$> direction on the (111) surface. Figure 7 shows an example of the measurement result of the profile curve of the specimen after the cutting experiment using a white light interferometer. From the figure, the difference in depth of cut at the beginning and end of cutting (10.5 mm length) was 10 nm, which indicates that high precision positioning was achieved by the alignment system. As the maximum nominal cut thickness (h_{max}) in this cutting condition was 1 µm, a high-quality optical surface (Sa=26.68 nm) without cracks and high transparency was obtained, as shown in Fig. 8.

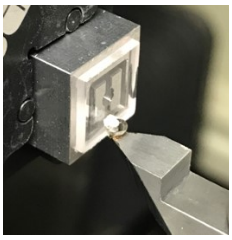

Figure 6 Diamond cutting of CaF_2

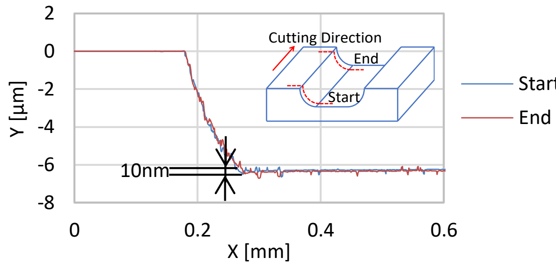

Figure 7 Profile curve of machined surface

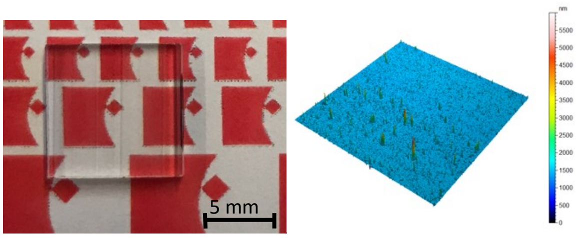

Figure 8 Diamond machined surface (left) and surface profile by white light interferometer(right)

5. Conclusion

A manual workpiece alignment system for diamond cutting of CaF_2 was developed and its performance was evaluated. Results verified that the developed system has sub-micrometer positioning resolution and sufficient rigidity to withstand cutting forces. Moreover, cutting experiments revealed the possibility of the system to achieve an error of cutting depth of 10 nm and as a result produce high quality optical surface.

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References

[1] H. Wang et al. 2016 Scripta Materialia **114** 21–26