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Experimental study of crystal anisotropy based on ultra-precision cylindrical turning of single-crystal calcium fluoride

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ABSTRACT

To realize ultimately efficient signal processing, it is necessary to replace electrical signal processing circuits with optical ones. The optical micro-resonator, which localizes light at a certain spot, is an essential component in optical signal processing. Single-crystal calcium fluoride (CaF_2) is the most suitable material for a highly efficient optical micro-resonator. The CaF_2 resonator can only be manufactured by ultra-precision machining processes, because its crystal anisotropy does not allow the application of chemical etching. However, the optical micro-resonator's performance depends definitely on the surface integrity.

This study investigated the relationship between surface quality after ultra-precision machining and crystal anisotropy. Firstly, crack initiation was investigated on the (1 0 0), (1 1 0), and (1 1 1) planes using the micro-Vickers hardness test. Secondly, brittle-ductile transition was investigated by orthogonal cutting tests. Finally, cutting performance of cylindrical turning was evaluated, which could be a suitable method for manufacturing the CaF_2 resonator. The most difficult point in cylindrical turning of CaF_2 is that the crystalline plane and cutting direction vary continuously. In order to manufacture the CaF_2 optical micro-resonator more efficiently, analysis was conducted on crack initiation and surface quality of all crystallographic orientations from the perspective of slip system and cleavage.

1. Introduction

The development of the optical transmission technique has increased the transmission speed of communication devices dramatically. Although a signal is transmitted as an optical signal, it currently needs to be converted into an electrical signal for signal processing purposes. Transmission speed decreases in electrical signal processing and energy loss occurs in an integrated circuit through heat. Extremely high processing speed and a reduction in energy loss could be achieved if a conventional signal processing circuit was replaced by an optical one. Optical micro-resonators localize light at certain spots and are essential for optical signal processing. While various semiconductor materials such as Silicon or SiO_2 are utilized for optical micro-resonators [1–3], CaF_2 [4] could be the most suitable material from an absorption coefficient viewpoint. Etching and irradiating with a CO_2 laser have been generally employed for the manufacturing process. However, the application of these processes to CaF_2 is hindered by two problems: the difficultly in controlling anisotropic etching for fabrication of a bulge-shaped resonator [5] and breakage of a single-crystal structure by laser heat. Additionally, the actual performance of the CaF_2 optical micro-resonator fabricated by these processes becomes lower than ideal.

The prospective and feasible CaF_2 resonator fabrication technique is ultra-precision turning and polishing, as shown by Maleki [6,7]. Although the polishing process is required to make the surface of a resonant part smoother, prolonged polishing reduces form accuracy. To shorten polishing time, it is necessary to make a smoother surface at the ultra-precision cutting process stage [8–11]. In addition, the single-crystal CaF_2's characteristics indicate hard brittleness and crystal anisotropy [12–14]. Yan [15] showed that crack initiation depended on cutting direction and that the

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critical depth of cut changed remarkably on the basis of the crystal orientation. Previous CaF_2 machining studies have focused on face turning, and showed that the crystalline plane was set to constant. For cylindrical turning on the other hand, which is the fabrication technique for the bulge-shaped resonator, the crystalline plane and cutting direction vary continuously.

The objective of this study was to analyze crack initiation and surface quality in terms of crystal anisotropy. Firstly, a micro-Vickers hardness test was performed to investigate the hardness and plastic deformation of CaF_2 on the (1 0 0), (1 1 0) and (1 1 1) plane. Secondly, orthogonal CaF_2 cutting tests were performed to examine brittle-ductile transition and the critical depth of cut. Finally, cylindrical turning was performed on CaF_2 workpieces with three crystal structures: end face orientation (1 1 1), (1 1 0), and (1 0 0). As crystalline plane and cutting direction vary continuously, crack initiation and surface quality could be analyzed from the perspective of slip system and cleavage for all crystallographic orientations.

2. Micro-Vickers test

2.1. Experimental setup

A micro-Vickers hardness test [16] was performed with a hardness testing machine (MVK-H12, Akashi), which enabled to control the load force (0.05–10 N). A CaF_2 workpiece (38.0 mm × 13.0 mm × 1.0 mm) was pre-polished to remove existing micro-cracks. The pyramidal shape of the indenter had an angle of 136° between opposite faces. It is important for crystalline material machining to produce plastic deformation and prevent crack initiation caused by cleavage. CaF2 generally has a fluorite-type crystal structure, in which the cleavage plane is {1 1 1} and the slip system is {1 0 0} <1 1 0>. In this test, the plastic deformation and crack initiation mechanisms were investigated from the slip system and cleavage perspective.

Table 1
Angles between each plane of a calcium fluoride structure.

Crystal plane	Angle between crystal plane orientation and slip plane	Angle between crystal plane orientation and cleavage plane
1 0 0	0.0, 90.0°	54.7°
1 1 0	45.0, 90.0°	35.5, 90.0°
1 1 1	54.7°	70.5, 109.5°

2.2. Plastic deformation and crack initiation

Fig. 1 shows the initiation of a crack on each plane viewed through an optical microscope (VH-Z100UR and VH-Z450, KEYENCE). Single-crystal CaF_2 exhibits a cubic structure (calcium fluoride structure). The angles of the slip and cleavage plane are listed in Table 1. In a general micro-Vickers hardness test, a crack appeared along the indenter corner and no cracks appeared along the indenter ridgeline. A crack emanated at load forces of 0.5, 1.0, and 5.0 N on the (1 1 0), (1 1 1) and (1 0 0) planes, respectively. Fig. 2 illustrates the mechanism of plastic deformation corresponding to the slip system and cleavage. On the (1 1 0) plane, cleavage planes existed at an angle of 0°, which corresponded to the indentation

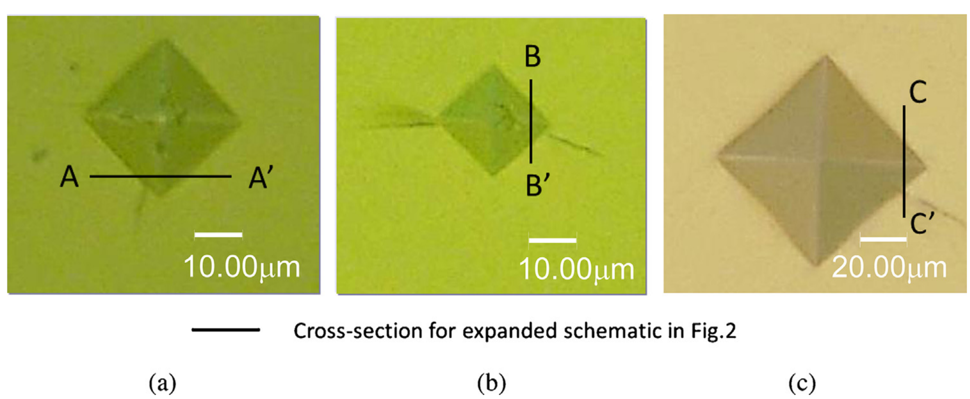

Fig. 1. Optical microscope images of the indentation, for (a) the (1 1 1) plane with a 1.0 N load force, (b) the (1 1 0) plane with a 0.5 N load force, and (c) the (1 0 0) plane with a 5.0 N load force.

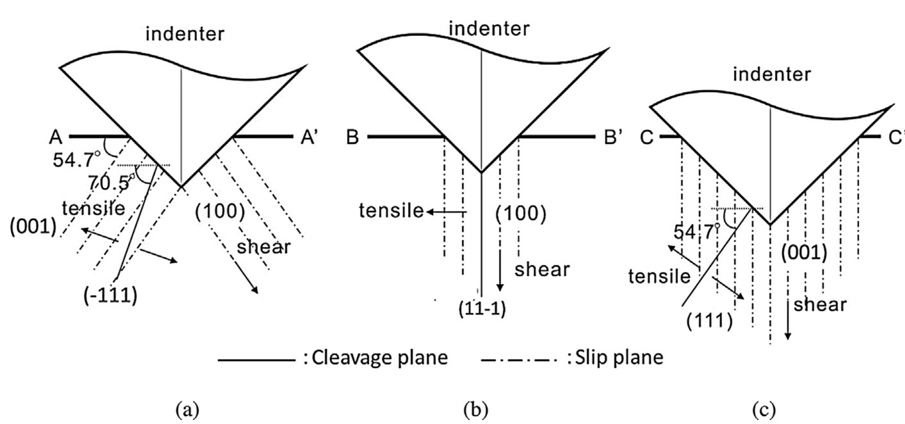

Fig. 2. Expanded schematic overview of the crack initiation mechanism, with (a) the (1 1 1), (b) the (1 1 0), and (c) the (1 0 0) plane.