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Experimental verification of lithium niobate cutting phenomena from the view point of crystallographic orientation

Hiroyuki Kodama[1], Koichi Okuda[1], Masaaki Harada[1], Tsunemasa Saiki[2] and Kazuya Hamaguchi[2]

[1]*University of Hyogo, Graduate School of Engineering, Japan*
[2]*Hyogo Prefecture Institute of Technology, Japan*

kodama@eng.u-hyogo.ac.jp

Abstract
Lithium niobate ($LiNbO_3$) has many characteristics including piezoelectric and nonlinear optical effects. It is used for making low-path filters, light modulation devices and surface acoustic wave (SAW) elements. A processing method using the lithographic technology is generally used for various semiconductor materials, including $LiNO_3$. However, this method entails high production cost and has low flexibility. Moreover, $LiNbO_3$ is a brittle material with crystal anisotropy. In a previous study, direct processing of $LiNbO_3$ using an end-mill and diamond cutting tool was used to improve production flexibility. However, the processed $LiNbO_3$ suffered surface deterioration and brittle destruction under normal tool cutting conditions. Therefore, the aim was to achieve ductile mode cutting of $LiNbO_3$ in relation to the critical depth of the cut for various cutting directions. Investigation of the SAW phenomena such as propagation on the $LiNbO_3$ substrate revealed that SAW reflection and transmission depends on the edge quality and cross-section shape of the micro-grooves. The SAW reflection diffusion was controlled by forming micro-grooves in the $LiNbO_3$ surface. However, the use of end-milling to form the grooves caused many cracks and fractures. To avoid this problem, the diamond cutting tool was operated in a planner-type line direction, and the micro-grooves were cut in the same way. However, micro-grooves with fine surface integrity could not be obtained. In the study reported here, the effect of the crystallographic orientation of the $LiNbO_3$ for planer-type line direction cutting with a diamond tool was examined in an effort to obtain fine surface integrity. The processing conditions needed to obtain ductile mode cutting and the mechanism generating brittle fractures of the $LiNbO_3$ surface were investigated by comparing the crystal construction calculated from visualization of the electronic and structural analysis results. Ductile mode cutting experiments demonstrated that 0° and 90° in relation to the flat orientation are more ductile directions.

Keywords: lithium niobate, crystallographic orientation, planer-type cutting, surface integrity

1. Introduction

Micromachining is a key technology in MEMS and the nano-technology fields. The focus in a previous report was on the fabrication of a micro-pump device driven by SAW phenomena in µ-TAS. An attempt was made to form micro grooves on a lithium niobate substrate using round-edge and straight-edge diamond cutting tools [1]. Cutting tests revealed that brittle fractures did not form when the cutting depth was less than a certain level (ductile mode cutting) and that the critical cutting depth depended on the cutting direction relative to the crystal orientation. The testing also revealed that the fractures were generated at the groove edges and bottoms, which substantially increased tool wear [2].

In the study reported here, microgroove machining using planer-type cutting with a round-edge diamond tool was performed to identify the ductile mode cutting effects from the view-point of crystallographic orientation and analysis results of visualization for electronic and structural analysis (VESTA).

2. Experimental method

The setup used for the cutting experiments is shown in Fig. 1. An ultra-precision vertical milling machine (UVM-450, Toshiba Machine) was used to cut the grooves. Specially designed single-crystal diamond tool had a round-edge with a radius of 0.8 mm and rake angle of 0°. The $LiNbO_3$ substrate had a flat orientation with respect to the reference surface. The table feed was 1000 mm/min, and the pick feed and depth of cut were both 1.0 µm. Under these conditions, the calculated (Hmax) is 0.049 µm. We defined the direction to the right as 0°, and counter clockwise as the positive direction. Since $LiNbO_3$ has a strong crystal orientation dependency, the anisotropy was assumed to affect the cutting characteristics. We observed the chip cutting examined the cut chips to investigate the anisotropy effect of ductile mode cutting.

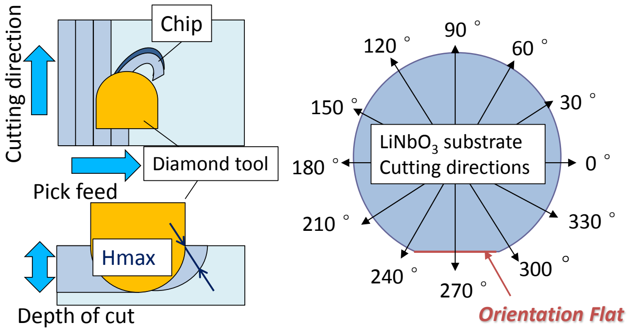


Figure 1. Schematic diagram of cutting experiments.

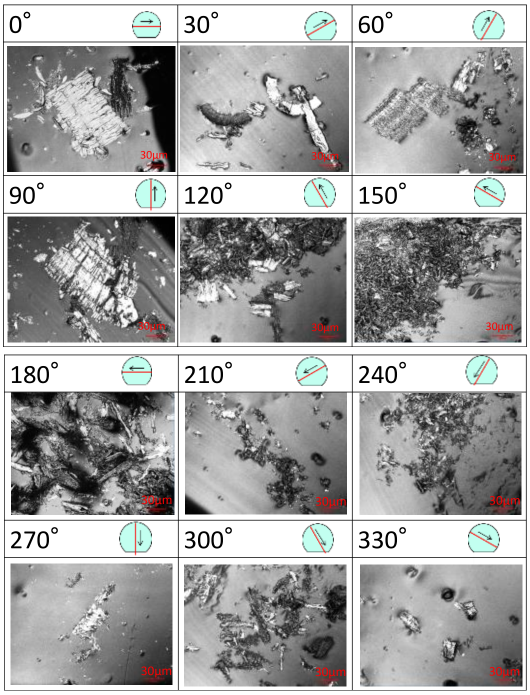


Figure 2. Images of chips formed for each cutting direction.

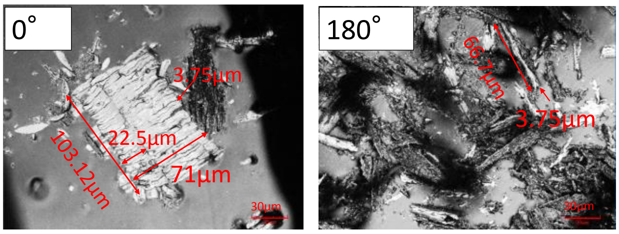


Figure 3. Estimated dimensions of chips.

3. Chip observation results

Images of chips for 12 directions are shown in Fig. 2. Those for 0° to 90° and for 330° exhibited continuous ductility. Those for 180° and 300° exhibited needle-shaped medium ductility. Those for 150° and 210° exhibited a powdery state (brittleness). Figure 3 shows the measured chip dimensions for 0° and 180°. For 0°, the chips were continuously composed of chips for 180° because the chip shape was almost the same between 0° and 180°. This means that the $LiNbO_3$ crystal structure affects chip shape formation. We repeated this cutting experiment for cutting directions of 0°, 150° and 180° and reduced the pick feed from 1.0 to 0.1 μm to obtain a more ductile shape chip. Figure 4 shows images of chips formed using the two pick feeds. It is evident that $LiNbO_3$ anisotropy must be considered when conducting ductile mode cutting. For 150° and 180°, because the depth of cut is less than the tool tip radius (0.8 mm), the powdery state was caused by tool tip burnishing. On the other hand, for 0°, the chip shape was continuous. Therefore, 0° is a more ductile direction.

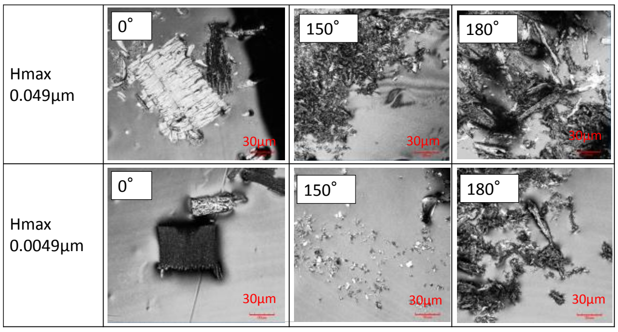


Figure 4. Images of chips formed using two values of Hmax.

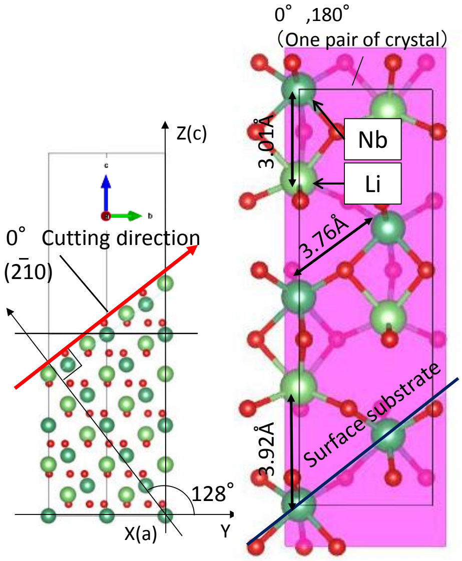
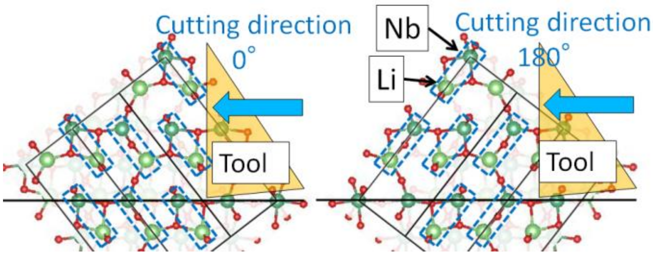


Figure 5. Crystal lattice of $LiNbO_3$ modelled by VESTA.



(a) o° (b) 180°

Figure 6. 2D cutting model for $LiNbO_3$.

4. Effect of crystal lattice on cutting process

Figure 5 shows the crystal lattice of $LiNbO_3$ modelled by VESTA. The Li and Nb on the cutting surface are in the Z direction. Therefore, the Li and Nb on the cutting surface form a robust bond. To investigate the effect of the crystal lattice on the cutting process, we created a 2D cutting model for $LiNbO_3$, as shown in Fig. 6. The arrangement of Li and Nb has the potential of creating crystal orientation dependency of the $LiNbO_3$. For the 0° direction, if Li and Nb form a band pair, the pair co-locates in the sliding direction. For the 180° direction, the band pair co-locates so as to block the passage from the sliding direction to the feed direction. These results show that the crystal lattice for each cutting direction affects the feasibility of ductile mode cutting.

5. Conclusion

The machining of micro-grooves using planer-type cutting with a round-edge diamond tool was done to investigate the feasibility of ductile mode cutting from the view-point of chip formation. Ductile mode cutting experiments demonstrated that 0° and 90° are more ductile directions.

References

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