euspen's 15th International Conference & Exhibition, Leuven, Belgium, June 2015
www.euspen.eu

Investigation of micro milling of lithium niobate for biosensor applications

Yilun Shi[1], Dehong Huo[1], Yan Zhao[1,2], Zeyad Yousif Abdoon Al-Shibaany[1], John Hedley[1]

1 School of Mechanical and Systems Engineering, Newcastle University, Newcastle Upon Tyne, NE1 7RU, UK
2 College of Mechanical Engineering, Yanshan University, 066004, China

y.shi12@newcastle.ac.uk ; dehong.huo@newcastle.ac.uk

Abstract
Lithium niobate ($LiNbO_3$) is a crystalline material which is widely applied in surface acoustic wave, MEMS, and optical devices, owing to its superior physical, optical, and electronic properties. Due to its brittle property, $LiNbO_3$ was considered as a hard-to-machine material. In this paper, we focused on applying the brittle-ductile transition phenomenon to accomplish machining $LiNbO_3$ in ductile regime, with the aim to obtain optimal process parameters. Machining of micro channels was performed on Z-cut $LiNbO_3$ wafers, by micro end milling, using both single crystal diamond and TiAlN coated tools. The cutting forces, surface quality and tool wear conditions were examined and characterised for analysis. In addition, the effect of the material's crystallographic structure over the machined surface quality is also studied. Finally, high quality crack-free surfaces were obtained under carefully selected cutting parameter sets.
Keywords: micro machining, lithium niobate, brittle-ductile transition

1. Introduction

The resonant based biosensor is the main part of a point-of-care diagnostic device, which is commonly designed and fabricated from crystalline material to give a high quality factor resonator. In order to overcome the high cost and relatively long initial preparing time of microfabrication methods, alternatives are being developed in manufacturing micro components, especially when producing small batch or prototypes. The flexibility, capability of generating complex microstructures, as well as the easy setup and versatility of micro-milling process, have made it a desirable solution.

Lithium niobate ($LiNbO_3$) has attracted attention from many researchers for its potential in being applied in such biosensors, due to the fact that it is superior to silicon based materials in terms of mechanical and electrical performance [1], which leads to higher sensitivities. However, due to the brittle properties of $LiNbO_3$, it is prone to suffer scratching and edge chipping when being machined, which could lead to serious defects of surface quality and performance. Therefore, applying the brittle-ductile transition phenomenon to accomplish machining $LiNbO_3$, in the ductile regime, was studied, aiming at the key techniques, such as optimal process parameters and crystallographic orientations.

2. Experimental procedure

The experimental setup and the working coordinates of the micro milling system is shown in Figure 1. Two series of micro channels were performed on Z-cut Lithium Niobate samples (dimension 10mm x 10mm x 0.5mm) by an ultra-precision CNC MTS5R. Both a two-flute TiAlN coated tool (ϕ0.3mm) and a single flute single crystal diamond tool (ϕ0.3mm) were utilized, for assessing the effect of tools. The machining parameters, namely feed rate, cutting speed and depth of cut, were included in a full factorial design, in order to evaluate their effects over the surface quality. Additionally, a set of micro channels along various directions were also performed on the sample under the same machining conditions.

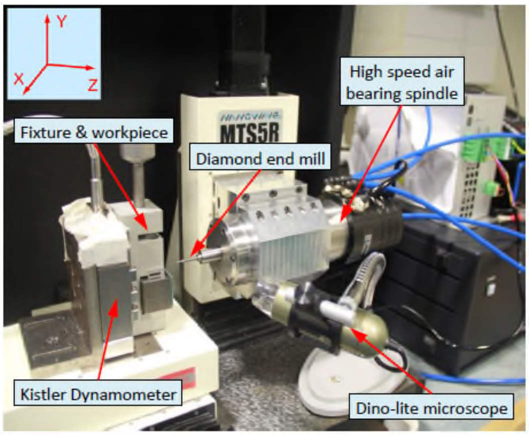

Figure 1. Experimental setup and working coordinates

The cutting forces were collected by a dynamometer during the process to calculate the specific cutting energy. An algorithm was also performed on the raw force data to obtain the principle cutting forces and thrust forces, via equation 1:

$$\begin{pmatrix} dFx(\theta) \\ dFy(\theta) \end{pmatrix} = \begin{pmatrix} -\cos\theta & -\sin\theta \\ \sin\theta & -\cos\theta \end{pmatrix} \begin{pmatrix} dFt(\theta) \\ dFr(\theta) \end{pmatrix} \quad (1)$$

where Fx and Fy represent the forces along the feed and normal directions respectively, while Ft and Fr represent the thrust and cutting forces, with θ as the rotation angle of the flute [2].

3. Results and discussion

3.1. Surface topography

Qualitive surface characterisation of the machined slots was performed using an SEM and a 3D surface profilometer. As shown in Figure 2, increasing the feed rate and/or cutting depth could result in thermal mechanical marks on the slot bottom surface which leads to defects. Also, decreasing the cutting speed will cause massive edge chipping. Additionally, replacing the diamond end mill by a TiAlN coated tool causes severe surface scratching. Later observations proved that the TiAlN tool was seriously worn after the experiments.

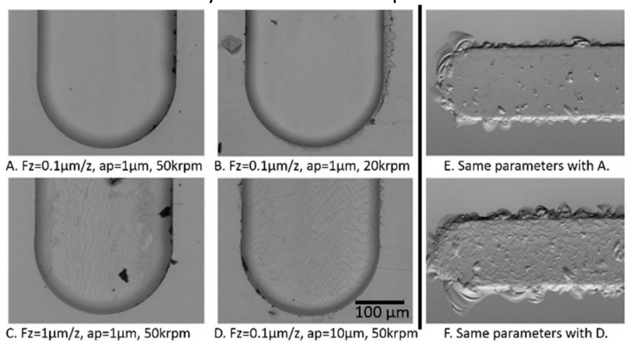

Figure 2. SEM pictures of micro channels. (A) Slot machined using optimized parameters; (B) Decreasing the cutting speed in A; (C) Increasing the feed rate in A; (D) Increasing the cutting depth in A; (E,F) Machining using the parameters in A and D with a UT coated tool.

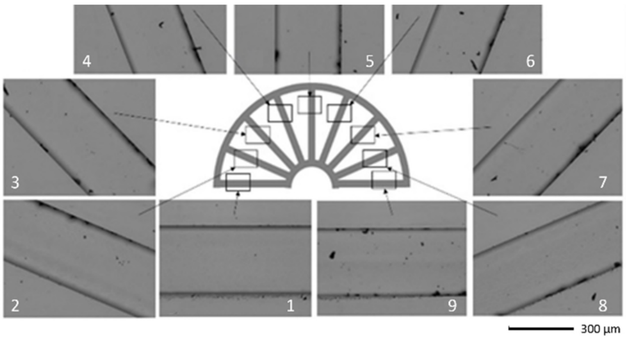

Figure 3. Crystallographic effect over the surface quality

In order to study the crystallographic effects of the material over the surface quality, channels in different orientations were machined under the same cutting conditions, and the layout is as shown in Figure 3. It was found that edge chipping occurred in the slots around the horizontal direction (No. 1,2,8,9 in Figure 3) and only on the bottom side edges, indicating that it did not originate from the difference between up-milling and down-milling. Clear tool marks on the slot bottoms and rigid edges were found in Pic 5-7, which are generally taken as signs of ductile mode cutting.

Finally, a close examination of the slot machined under optimal conditions showed the result as in Figure 4.

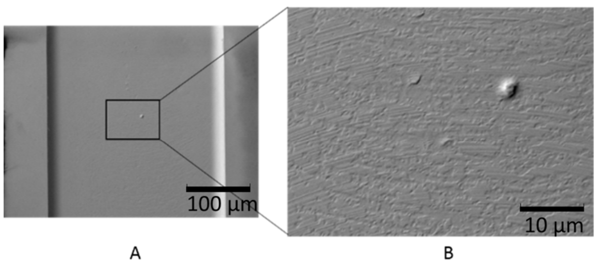

Figure 4. (A) Bottom of the slot machined under optimal parameters, pocessing rigid edges and smooth, polishing-like surface; (B) Zoom-in view of Pic A, magnified by a total of 3 000 times, where tool marks are clearly visible, indicating that ductile mode machining was undergoing when producing this micro channel.

3.2. Cutting force analysis

The specific cutting energy, or specific cutting force required by plastic deformation of the material, is lower than that required by brittle rupture [3]. Thus it would also be an indication of brittle-ductile transition occurring should a drop of the specific cutting force be observed. The specific cutting energy (unit: MPa) is defined as follow:

$$\mathrm{Uc} = \frac{Vc}{Vrem} \times \int_0^{Tc} \sqrt{Ft^2 + Fc^2}\, dt \qquad (2)$$

where V*c* and V*rem* stand for the cutting speed and material removal volume, with Tc as the cutting time.

ANOVA performed on an algorithm of cutting force data (Figure 5) indicates, with a strong confidence, that within the experimental machining conditions, both the depth of cut and the feed rate have negative influence on specific cutting energy, and higher cutting speed results in higher values. Therefore, lower specific cutting energy, which has been assumed as a sign of ductile machining is obtained with higher cutting speed, along with a smaller feed rate and cutting depth. This conclusion is consistent with the results from surface topography analysis. However, the theory that under a critical uncut chip thickness, the thrust force stays larger than the principle cutting force [4] is not supported by the results from the experiments.

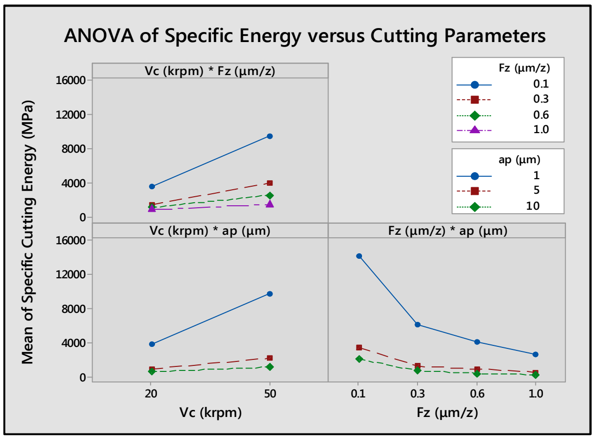

Figure 5. Factorial plots of specific cutting energy v.s. cutting parameters

4. Conclusion

Ductile micro milling on Lithium Niobate can be performed using a single crystal diamond end mill with a small feed rate (0.1 μm/z) and depth of cut (1 μm~5 μm) and relatively high cutting speed, of which the feed rate is the crucial factor. The results from both surface topography and cutting force analysis are consistent with each other. The crystallographic orientation also has an effect over the surface quality. TiAlN coated end mills are not capable of fabricating precise micro features on this material.

Acknowledgement

The authors wish to thank EPSRC (EP/M020657/1 and EP/K031953/1) for the support for this work. The authors are also grateful to Air Bearing Ltd for providing the high speed spindles used in the experiments.

References

[1] Ortiz P, Burnett R, Keegan N, Spoors J, Hedley J and Harris A, 2012 Issues associated with scaling up production of a lab demonstrated MEMS mass sensor *J. Micromech. and Microeng*, **22** 11

[2] Kang I S, Kim J S, Kim J H, Kang M C and Seo Y W, 2007 A mechanistic model of cutting force in the micro end milling process. *J. Mater Process Tech*, **187** 250-5.

[3] Wang J J J and Liao Y Y, 2008. Critical depth of cut and specific cutting energy of a microscribing process for hard and brittle materials. *J. Eng Mater-T ASME*, **130(1)**, 011002.

[4] Davim J P 2008. *Machining: fundamentals and recent advances.* 145, Springer.