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A new process chain for ultra-precision machining potassium dihydrogen phosphate (KDP) crystal parts

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Abstract
Potassium dihydrogen phosphate (KDP) crystal parts used in high power laser systems require high figure accuracy and high laser induced damage threshold (LIDT). However KDP crystal is extremely soft, hygroscopic, brittle and thermally sensitive, which make it difficult to meet the requirements via conventional processing methods. This paper puts forward a new process chain for ultra-precision machining KDP crystals, including single point diamond turning (SPDT), magnetorheological finishing (MRF) polishing and ion beam figuring (IBF) polishing processes. A compensation SPDT process is developed as the first step of the process chain to reduce machining errors (due to vacuum suction force, spindle unbalance, etc.). As a result high shape accuracy and fine surface roughness is obtained with high machining efficiency Non-aqueous and abrasive-free MRF polishing process is then employed to remove the diamond turning marks and further improve shape accuracy and increase the LIDT. Ion beam figuring (IBF) polishing is introduced as the final step of the process chain to remove the impurity layer. Experiments are carried out to evaluate the effectiveness of the proposed ultra-precision process chain.

Potassium Dihydrogen Phosphate (KDP), Ultra-precision Machining, Single Point Diamond Turning (SPDT), Magnetorheological Finishing (MRF), High Power Laser Systems, Laser Induced Damage Threshold (LIDT)

1. Introduction

Potassium dihydrogen phosphate (KDP) crystals, which served as electro-optics switchers and frequency converters, play an important role in high power laser systems. The high-power laser system has serious requirements for the optical properties of KDP crystal. Its high-frequency error will affect the laser damage threshold and increase the scattering loss. The high power laser system requires a surface accuracy of better than $\lambda/6$ (λ=632 . 8 nm), PSD1 better than 5 nm, and the surface roughness better than 1.5 nm. Single point diamond fly-cutting is one feasible fabrication method. At present, it is difficult to ensure stable processing to meet all the requirements.

This paper puts forward a new process chain for ultra-precision machining KDP crystals, including single point diamond turning (SPDT), magnetorheological finishing (MRF) polishing and ion beam figuring (IBF) polishing processes.

2. SPDT and error compensation

First, we plan to adopt SPDT to get the initial workpiece. By using SPDT, surface figure error and roughness are trying the best to achieve.

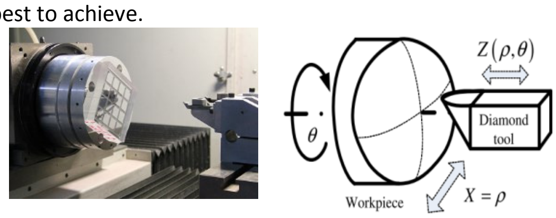

Figure 1 Schematic of SPDT and error compensation machining method

2.1. Ductile turning of KDP crystals

Scholars did extensive researches on ductile regime cutting mechanism of brittle materials [1]. They summarized the indentation model of brittle materials established by Lawn and suggested the condition to achieve ductile regime material removal, namely that there exists a critical depth of cut d_c, and ductile regime material removal can be achieved if the removal thickness of the brittle material is less than d_c.

KDP crystals show obvious anisotropy and the modulus varies periodically from the change of crystals' orientations. The critical depth of cut to achieving ductile material removal changes with different cutting directions. Therefore, in order to get full aperture ductile surface, cutting parameters must be controlled to ensure strictest condition around all cutting directions.

2.2. The compensation of deformation error

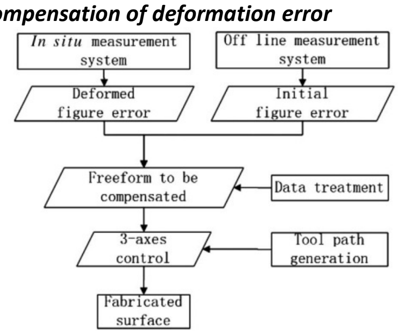

Figure 2 Schematic of compensation procedure

Because the error distribution to be compensated is commonly free-form, the compensation of deformation error is equal to fabrication of a free-form surface that can be achieved by employing the three-axis servo control technique [2], as shown in Fig. 1. First, the free-form surface is depicted by cylinder coordinate; then, realizing simultaneous motion of C, X, and Z-axis helps to generate the free-form surface shape. It is obvious that the exactness of compensation process is determined by the machine servo accuracy, in situ measurement accuracy, and the ambient environment.

3. MRF polishing

Second, non-aqueous MRF polishing is employed to improve surface accuracy [3], as shown in Fig. 3. The traditional polishing methods are difficult to fabricate the KDP crystals due to their special characters, such as softness and deliquescence. For example, the removal mechanism of traditional MRF polishing utilizes shear stress to complete material removal when abrasive particles are embedded in the surface under pressure. With traditional MRF polishing, it is easy to generate an obvious scratch because of the low hardness of KDP crystals. The abrasive particles are easy to embed into the surface.

Based on the water-solubility of KDP crystal, we add a small amount of deionized water in magnetorheological fluid to replace the traditional polishing abrasive particles. The removal efficiency is stable when water content, polishing pressure, relative speed, and temperature are stable. Thus, we can achieve a deterministic process based on controlling the dwell time. The MRF carrier liquid with stable chemical properties constitutes a great proportion of the MRF-polishing fluid, and water accounts for only a small proportion. Thus, there are only a few water molecules in contact with KDP, and they are taken away quickly to avoid the fogging of the KDP crystal.

Figure 3 MRF-polishing

Figure 4 IBF polishing

4. IBF polishing

Then, ion beam figuring (IBF) based on low energy ion sputtering was put forward to bombard KDP surface polished by MRF [4], as shown in Fig. 4. Magnetorheological figuring (MRF) is one of the ultra-precise machining methods for KDP crystal, but iron powders from magnetorheological fluid may be embedding into the soft KDP crystal. IBF polishing is a kind of noncontact polishing. KDP crystal can avoid fogging for IBF polishing if the process is performed in a vacuum environment. It can meet all the important requirements, removing residual impurity on the surface, without introducing new impurities, and without damaging the surface quality. KDP crystal is classified as a heat-sensitive material. IBF polishing will form a locally high temperature that can easily result in crystal cracking. So small-diameter and low-energy beam were used. The IBF polished surface is clean, without residual MR fluids.

The changes of crystal structures and surface roughness of KDP before and after IBF were analysed by Raman spectral analysis technology and white light interferometer, respectively. Moreover, surface elements of KDP crystal machined by MRF, IBF were researched through secondary ion mass spectroscopy (SIMS) analysis. The results indicated that crystal structure is not changed and the roughness is improved by low energy ion sputtering, which means that IBF could be used for machining KDP crystal. After IBF the iron powders on the surface of KDP crystal are cleaned on the whole.

5. Experiments

By using the new process chain, we machined an 100mm by 100mm KDP sample. The experiment results are list as Figure 5. Compared to NIF specification system, all the requirements in geometry are satisfied.

Table 1 The experiment results of new process chain

	TWFE PV(λ)	GRMS (nm/cm)	PSD1 RMS(nm)	PSD2 RMS(nm)	Roughness RMS(nm)
100X100	0.063	8.3	4.83	1.16	1.4
NIF	0.167	11	5	1.5	1.5

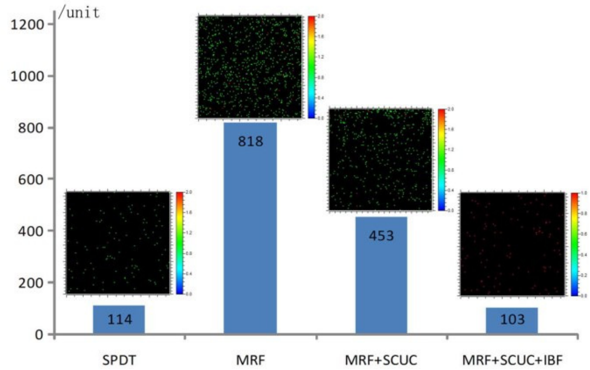

Figure 5 Content of Fe element after different process.

The content of Fe element on the KDP surface after a different process is measured [5]. The results are shown in Fig. 5. The small punctuate particles on the picture reveals the distribution of impurity elements. The measurement is relative; the number does not denote absolute content of the Fe element.

The results show that the content of the Fe element contamination on the MRF polished surface increases a lot compared to the SPDT. It decreases a few units after a ultrasonic cleaning (SCUC). It decreases to 103 units after IBF polishing. This means after MRF polishing, a post polishing is needed, applying IBF to remove pitting and the Fe-residuals caused by the previously applied by MRF polishing process. Fe contamination on the processed KDP crystal surface has reduced to a standard low enough after IBF polishing process.

6. Conclusion

Full aperture ductile turning is accomplished by reasonable control of cutting parameters. Compensation turning method successfully avoids the figure error transferring from datum planes of vacuum chuck. The non-aqueous MRF polishing can effectively eliminate the cutting texture and achieve better surface figure and roughness. IBF polishing can effectively remove the Fe residual contamination on the KDP surface after MRF polishing.

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