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Research on error compensation for curved polishing of KTP crystal

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Abstract

With the continuous advancement of laser technology, the demands for surface quality and precision of $KTiOPO_4$ (KTP) material, which is a crucial nonlinear optical material, are becoming increasingly stringent. To effectively control surface accuracy during the polishing of KTP crystals, this paper presents a novel machining approach based on error compensation. The proposed method achieves an ultra-smooth surface with an *R*-value error of less than 1% and surface roughness *S*q 1.23 nm for KTP components.

Keywords: $KTiOPO_4$; Surface roughness; Surface accuracy; Error compensation

1. Introduction

Potassium titanyl phosphate ($KTiOPO_4$, KTP) is a crucial nonlinear optical material, renowned for its high optical damage threshold, stable chemical properties, resistance to deliquescence, and exceptional mechanical strength. KTP crystals are commonly synthesized via high-temperature solution methods or hydrothermal techniques [1]. These crystals exhibit remarkable physical and optical characteristics, including a nonlinear optical coefficient approximately 15 times greater than that of KDP crystals. Their wide acceptance angle and small walk-off angle provide distinct advantages in nonlinear optical applications. Additionally, KTP crystals are essential in the fabrication of optical waveguide devices, which are pivotal in optical communication, optical information processing, and other fields. Surface smoothness is a critical factor influencing the optical performance of KTP crystals. A smoother surface reduces light scattering and loss, thus enhancing the conversion efficiency and stability of optical components. As manufacturing technologies advance towards higher precision and automation, the demands for optical components with superior performance are growing. Consequently, there is an increasing need for KTP crystals with smooth surfaces and well-defined shapes, which requires further refinement of current processing methods to meet the desired surface quality and geometric precision.

In the process of polishing KTP crystal, there are challenges that the polishing effect is not good and the surface shape cannot reach the ideal state. To achieve KTP crystals with an ideal surface shape and smoothness, polishing is an effective technique. Yuan et al. [2] introduced a novel approach for polishing KTP materials using a super-precision planar polishing machine, combined with fine Al_2O_3 and SiO_2 abrasives, which resulted in a final surface roughness of less than 1 nm. Dieste et al. [3] explored two distinct research paths involving a tool with both rotational and translational motion, with dry abrasives mounted at the tool's front end. This work focused on developing a predictive model for surface quality parameters and analysing the material removal rate (MRR) based on polishing parameters, enabling the prediction of tool footprint during the polishing process, thereby achieving conformal polishing. Gong et al. [4] conducted a series of chemical mechanical polishing (CMP) experiments on the Si surface of 4H-SiC, using an orthogonal design of Al_2O_3 abrasive slurry. They studied the effects of pH, abrasive concentration, and oxidant content on the material removal rate. Li et al. [5] examined the influence of various polishing parameters on wafer surface quality and optimized the CMP process to improve the surface finish. Their research led to the achievement of a surface roughness of Ra 0.81 nm, enabling efficient and precise polishing of GaN wafers. Guo et al. [6] found that a uniform and ultra-smooth KTP crystal surface could be obtained when the SiO_2 particle size in the polishing slurry was 20 nm, the SiO_2 mass fraction was 10%, the pH was 10, and the H_2O_2 mass fraction was 3 wt.%.

To address the challenge of maintaining surface shape accuracy during KTP structure polishing, this paper proposes a polishing method incorporating an error compensation step for KTP machining. This approach is calculated by the formula of the new geometric relationship, allowing the polished KTP structure to achieve surface roughness *S*q 1.23 nm and a surface shape radius of 12.1 mm, resulting in KTP crystals with both a smooth surface and ideal shape.

2. Method and principle

2.1 Spherical machining method

The polishing process was conducted using a custom-designed five-axis precision motion platform, as illustrated in Figure 1. The platform allows for high-precision adjustment of the relative position between the polishing tool and the workpiece along the X, Y, and Z axis through a computer-controlled system. The polishing tool was designed to match the theoretical curvature of the KTP element, with a radius of 12 mm, and was mounted on the C-axis of the motion platform to ensure stable tool movement during operation. The KTP workpiece used in the experiments had dimensions of 2 mm × 1 mm × 10 mm. To minimize vibrations and enhance the stability of the workpiece during polishing, it was fixed onto the main spindle fixture using paraffin wax. This setup helped reduce potential damage caused by dynamic loads during the grinding and polishing process. During the polishing process, the rotational speed of the polishing tool was set to 400 rpm, while the abrasive tool rotated at 200 rpm. A constant downward force of 400 N was applied as polishing pressure. The polishing slurry consisted of 20 nm SiO_2 abrasive particles (10 wt.%), H_2O_2 (3 wt.%), and deionized water, with the pH adjusted to 10 to optimize the chemical mechanical polishing performances.

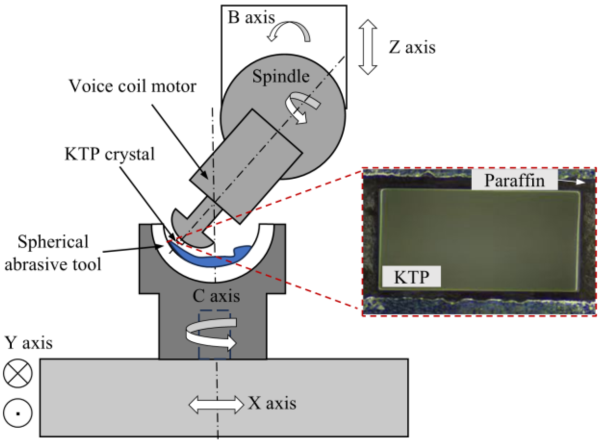

Figure 1. Diagram of the KTP spherical processing setup

2.2 Error compensation method

During the grinding process, an error typically arises between the radius of the workpiece after initial grinding and the ideal radius. To achieve the desired ideal radius, error compensation steps are necessary. The principle of error compensation is illustrated in Figure 2. The error compensation equation is as follows:

$$\begin{cases} x^2 + \left(\Delta + \frac{b}{4}\right)^2 = r^2 \\ (x + h_a)^2 + \Delta^2 = r^2 \end{cases}$$

h is the sagittal height, *b* is the width of the KTP crystal, *Δ* denotes the deviation between the theoretical and actual positions, and *r* represents the curvature radius of the KTP surface. h_a is the actual sagittal height after grinding and polishing, while h_i is the ideal sagittal height based on the design, which is 42 μm. There is an error between h_i and h_a. According to this equation, the value of Δ and x can be solved by bringing the actual measured values of h_a, b and r. And then bringing the ideal h_i into the above equation, the compensation radius can be solved. The KTP element with ideal radius and smooth surface can be obtained by grinding and polishing the KTP crystal again according to the compensated radius.

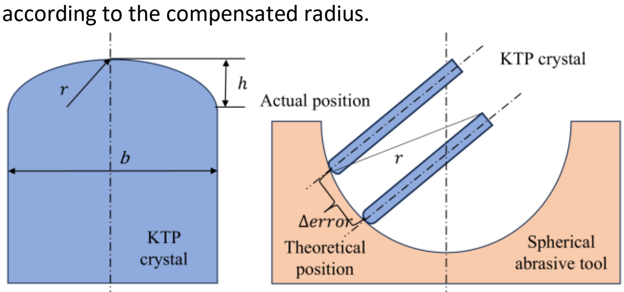

Figure 2. Error compensation diagram in polishing process

3 Results and discussion

3.1 Surface form accuracy

The surface contour data obtained is fitted to the spherical radius data using MATLAB software. Before error compensation, the surface radius of the KTP workpiece deviated from the ideal shape, measuring approximately 7.5 mm, as shown in Figure 3. After error compensation, the surface contour radius improved significantly, with the fitting result reaching approximately 12.1 mm, and the radius error was reduced to less than 1%.

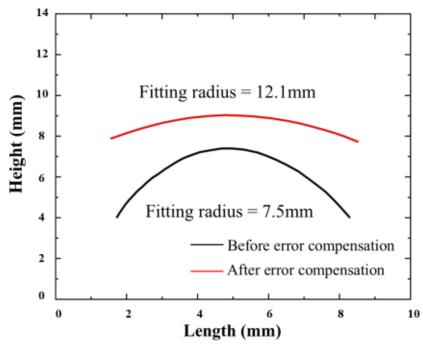

Figure 3. KTP crystal radius value before and after error compensation

3.2 Surface quality

After grinding, the KTP crystal undergoes further polishing, resulting in the elimination of pits, scratches, and other surface defects, as shown in Figure 4. The surface roughness decreases significantly from an initial *Sq* 90.75 nm to *Sq* 1.23 nm, as illustrated in Figure 5.

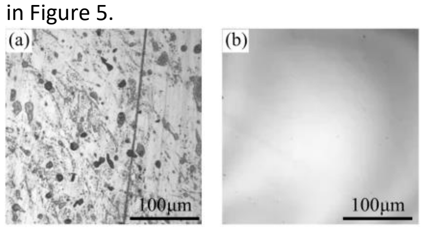

Figure 4. Surface morphology (a) before polishing; (b) after polishing

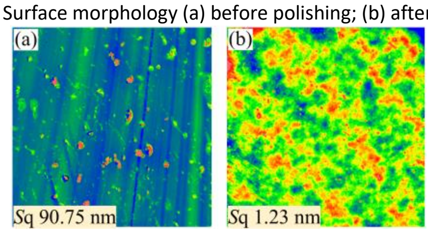

Figure 5. Surface roughness (a) before polishing; (b) after polishing

4 Conclusion

This paper presents a machining method for KTP crystal spheres based on error compensation. By precisely setting the tool and compensating for displacement through geometric analysis and calculations, the surface quality of the KTP crystal is significantly improved during the polishing process. Ultimately, the radius error of the KTP element is reduced to less than 1%, and the surface roughness is achieved to *Sq* 1.23 nm.

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