Research on thermal effect of KDP crystal under ion beam cleaning

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Abstract. KDP crystal is difficult to fabricate for high precision. Because it is brittle soft and with high heat expansion. Magnetorheological finishing (MRF) has been used to machine KDP for high precision. However, iron powders are easily embedded into KDP surface. Ion beam figuring (IBF) can clean iron powders embedded and enhanced laser-induced damage resistance. However, the thermal effect introduced by incident ions is a headachy problem. Temperature fields have been calculated by finite element simulation and measured by experiments. Thereof temperature fields of optical component bombarded by low energy ion beam were estimated and this estimate method is proved to be correct and feasible by comparing results of finite element simulation and experiments. And then, thermal stress of KDP under ion beam irradiation was calculated and discussed. Distributions of temperature and stress on KDP surface are accordant with beam current distribution. Temperature and stress rise quickly under ion beam irradiation, while decreases rapidly without ion beam irradiation. Peaks of temperature and thermal stress tend to periodicity. The period corresponds the period of ion beam moving spasmodically and fleetly in Y direction. Tensile stresses are not visible at X/Y/Z direction, but compressive stress at X direction is larger obviously than that of Y/Z direction.

1. Introduction

KH₂PO₄ (KDP) crystal is a kind of optical crystal for laser frequency conversion unit in the optical system such as Inertial Confinement Fusion (ICF) [1-3]. However, KDP is difficult to machine with high precision due to material properties such as anisotropy, softness, brittle and high heat expansion [4].

Currently, KDP is widely machined by single-point diamond fly-cutting and turning [5,6]. But, grains of cutting are inevitably appeared on the machined surface, which will constrain further improvement of the quality of machined surface. Especially, ripples with micro-scale degrade the laser-induce damage resistance [7,8]. Cutting grains and micro-scale ripples can be erased by Magnetorheological finishing technique [9-11]. However, iron powders in Magnetorheological fluid are easily embedded into soft KDP crystal. Fortunately, these iron powders can be cleaned and laser induced damage resistance can be enhanced after ion beam figuring (IBF) [12,13]. However, the thermal effect must be regulated in IBF for KDP crystal. Energy from incidence ion will heat the optics [14]. And crack or break will happen due to thermal stress [15]. Thus, it is important to reduce thermal effect in ion beam cleaning.
Firstly, distributions of temperature and thermal stress under ion beam radiation must be researched for this problem. Precedingly, our team researched the model of energy deposited and temperature field on optics under ion beam bombardment [16-18]. In this paper, temperature fields under ion beam bombardment are calculated by ANSYS and infrared thermal imager. Comparing with results of experiments, it is proved to be correct and feasible to evaluate temperature field by finite element simulation. And then, thermal stress under ion beam radiation was calculated and discussed.

2. Ion beam cleaning procession and research method

2.1. Ion beam cleaning procession

Fig. 1 shows ion beam irradiates optical workpiece in Z direction [17]. Distribution of beam current obtains Gaussian shape. IBF is aimed at cleaning iron powder embedded from MRF by removing the contaminative layer with uniform depth. ion beam directly bombards toward KDP surface in vacuum by raster-scanning the surface with a constant velocity. As shown in Fig. 2, in X direction, ion beam continuously moves with uniform speed, while spasmodically and fleetly in Y direction.

![Figure 1. workpiece under ion beam irradiation](image)

![Figure 2. Scanning path of ion beam cleaning](image)

2.2. Numerical and experimental methods

Experiments were implemented on KDIBF700-5V. Distribution of temperature was measured by FLIR SC7000, an infrared thermal imager. In order to prevent KDP from breaking or cracking, fused quartz was used under static ion beam for replacement. Sizes of optical components are both 100×100×10 mm.

In experiment, incidence ion is $\text{Ar}^+$ ion with energy of 600 eV. For KDP, the thermal source simulated by TRIM progress is 

$$P = 14256 \exp \left(-\frac{x^2 + y^2}{2 \times 0.009^2}\right)$$  \hspace{1cm} (1)

Temperature fields were calculated using ANSYS (APDL). And results from ANSYS were compared with results from FLIR SC7000 in actual measurement.

3. Result and discussion

3.1. Temperature field and thermal stress under stationary ion beam

In previous literature [17], we studied the temperature field of fused quartz from simulation and experiment with quiescent ion beam bombardment, as shown in Fig. 3. The temperature distribution is circular in fact, due to 45° angle between the camera of FLIR SC7000 and optical surface. The highest value of temperature occurs at center of optical surface. Temperature reduces along the radial gradually, based on ion beam current density.
Figure 3. Temperature field of fused quartz under quiescent ion beam at t=60s: (a) result from ANSYS; (b) experimental result from FLIR SC7000

Fig. 4 shows curves of temperature along radial direction of at various times [17]. Solid lines are results from ANSYS, while results from FLIR SC7000 are expressed by dots. Results are matched well. So, it is feasible to simulated temperature fields by ANSYS. Temperature of optics rises along with the increasing of time of ion beam radicalization. Characters of temperature distribution is accordant with beam current distribution.

Figure 4. Temperature distribution along radial direction with quiescent ion beam

Fig. 5(a) shows the radial stress at various times, while Fig. 5(b) and Fig. 5(c) show the axial stress and circumferential stress, respectively. Characters of stress distribution on KDP surface along X-axis accord with beam current distribution. It means compressive stress when the value is negative, while means tensile stress as the value is positive. The stresses enlarge with time incrementing under ion beam irradiation. As shown in Fig. 5(a) and Fig. 5(b), the peak of radial stress and axial stress appears at the center of ion beam and then decay along the radial gradually. The difference between the value of radial stress and axial stress is based on material properties of anisotropy. As shown in Fig. 5(c), circumferential stress tends to be positive from negative at R≈21mm, about the half of full width half maxim (FWHM) of Gauss function of beam current density, defined as follow

\[
FWHM = 2\sqrt{2}\ln 2\sigma = 2\sqrt{2}\ln 2 \times 9 \approx 21.2 \text{ (mm)} \tag{2}
\]
Figure 5. Curves of thermal stress: (a) radial stress; (b) axial stress; (c) circumferential stress

3.2. Temperature field and thermal stress under linear moving ion beam

When ion beam is moving along X axis direction on the surface, simulated and experimental temperature distribution on KDP crystal surface are shown in Fig. 6(a) and Fig. 6(b), respectively.

Figure 6. Temperature distribution of KDP crystal acted by liner moving ion beam:
(a) result from ANSYS; (b) result from FLIR SC7000

Fig. 7 shows curves of temperature rising along the path of ion beam center when ion beam moving with various speeds. With the decreasing of scan speed, the more time consumed when ion beam moving through the unit distance, the more heat energy stored on KDP crystal surface, leading to higher temperature.

Fig. 8 shows curves of temperature along the path of ion beam center when ion beam moving to various positions with speed of 0.0033 m/s. Temperature rises quickly under by ion beam irradiation, while decreases rapidly as ion beam moving out. The peak of temperature tends to be stable as ion
beam enter the KDP crystal surface absolutely, as shown in Fig. 9. The apophysis at t = 41s is cased of boundary effect when ion beam moving out.

**Figure 7.** Temperature curves with various speeds  
**Figure 8.** Temperature curves at various positions

**Figure 9.** Curve of the peak of temperature  
**Figure 10.** Curves of the peak of thermal stress

Fig. 10 shows the Curves of the peak of thermal stress at X/Y/Z direction. Stresses rise quickly as ion beam moving in, while decrease rapidly as ion beam moving out. Peaks of stress tend to be stable as ion beam enter the KDP crystal surface absolutely, same as the tendency of the peak of temperature shown in Fig.9. Tensile stresses are not visible at X/Y/Z direction, but compressive stress at X direction is larger obviously than that of Y/Z direction.

3.3. Temperature field and thermal stress under scanning moving ion beam

Fig. 11 shows temperature fields on KDP surface under scanning moving ion beam [17]. The temperature field from ANSYS is the same as that from FLIR SC7000. Three points, as shown in Fig.11, were selected. Fig.12 shows temperature curves of the three points during ion beam cleaning. Results from ANSYS and experiment match well. For each point, temperature rises swiftly under ion beam irradiation, and decreases rapidly with ion beam moving out. It is identical to above section.

Fig. 13 shows a curve of the peak of temperature while Fig. 14 shows that of stress. Peak of temperature and thermal stress tend to periodicity. And the period corresponds the period of ion beam moving spasmodically and fleetly in Y direction shown in Fig.2. The apophysis when ion beam moving in and out the surface is cased of boundary effect.
Figure 11. Temperature fields of KDP during ion beam cleaning: (a), (b) and (c) are results from ANSYS while (d), (e) and (f) are results from FLIR SC7000 at t=85.5s, 137.6s, t=194.9s, respectively

Figure 12. Temperature curves of point 1, 2 and 3

Figure 13. Curve of the peak of temperature

Figure 14. Curves of the peak of thermal stress
4. Conclusion

In this paper, temperature fields have been calculated by finite element simulation and measured by experiments. And then, thermal stress of KDP crystal under ion beam bombardment was calculated and discussed.

(1) Temperature fields of optical component bombarded by ion beam were estimated and this estimate method is proved to be correct and feasible by comparing results of finite element simulation and experiments.

(2) Characters of temperature and stress distribution under ion beam accord with profiles of beam current distribution.

(3) Under linear ion beam, Temperature and stress rise quickly under by ion beam irradiation, while decreases rapidly as ion beam moving out. The peak of temperature tends to be stable as ion beam enter the KDP crystal surface absolutely. Tensile stresses are not visible at X/Y/Z direction, but compressive stress at X direction is larger obviously than that of Y/Z direction.

(4) Under scanning ion beam, peaks of temperature and thermal stress tend to periodicity. The period corresponds the period of ion beam moving spasmodically and fleetly in Y direction.

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