Study on characteristic parameters influencing laser-induced damage threshold of KH_2PO_4 crystal surface machined by single point diamond turning

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It has fundamental meaning to find the elements influencing the laser-induced damage threshold (LIDT) of KH_2PO_4 (KDP) crystal and to provide suitable characterization parameters for these factors in order to improve the LIDT of KDP. Using single-point diamond turning (SPDT) to process the KDP crystal, the machined surface quality has important effects on its LIDT. However, there are still not suitable characteristic parameters of surface quality of KDP to correspond with the LIDT nowadays. In this paper, guided by the Fourier model theory, we study deeply the relationship between the relevant characteristic parameters of surface topography of KDP crystal and the experimental LIDT. Research results indicate that the waviness rather than the roughness is the leading topography element on the KDP surface machined by the SPDT method when the LIDT is considered and the amplitude of micro-waviness has greater influence on the light intensity inside the KDP crystal within the scope of dangerous frequencies between $(180\ \mu\text{m})^{-1}$ and $(90\ \mu\text{m})^{-1}$; with suitable testing equipment, the characteristic parameters of waviness amplitude, such as the arithmetical mean deviation of three-dimensional profile S_a or root mean square deviation of three-dimensional contour S_q , are able to be considered as suitable parameters to reflect the optical quality of the machined surface in order to judge approximately the LIDT of the KDP surface and guide the machining course. © 2011 American Institute of Physics. [doi:10.1063/1.3664692]

I. INTRODUCTION

Potassium dihydrogen phosphate (KH_2PO_4 , KDP) crystal is extensively used for harmonic generation, electro-optic switching in the terminal optical system of Inertial Confinement Fusion (ICF), its good nonlinear properties, and larger electro-optic coefficient.^{1,2} However, comparing with the theoretical laser-induced damage threshold ($147 \sim 200\ \text{J}/\text{cm}^2$, $1 \sim 3\ \text{ns}$), the current lower laser-induced damage threshold (LIDT) of KDP crystal (about $12\ \text{J}/\text{cm}^2$, $3 \sim 5\ \text{ns}$ in our experiment) has immensely limited the effective application and development of ICF.³ It is extremely necessary to find and study in depth the elements influencing the LIDT of KDP crystal and to provide suitable characterization parameters for them for improving the LIDT of KDP. Nowadays, studies on the LIDT of KDP crystal are most focused on the factors inside KDP crystal, such as stationary-state and transient-state deficiency inside the crystal,⁴ the inner impurity⁵ and scatter particles,⁶ the mechanism of the emerging and stabilizing of electron-hole, multi-photon ionization, and collision ionization.⁷ However, the machining qualities of the surface and subsurface of KDP crystal also have important effects on its LIDT, such as waviness, surface roughness and the subsurface defects, etc.

Because KDP is soft and brittle, and it is extremely easy for deliquescence, single-point diamond turning (SPDT) is the best method to process it now. However, this method will introduce obvious mid-frequency waviness on the KDP

surface along the cutting path (named micro-waviness). The micro-waviness is the remarkable feature of the KDP surface, and it will modulate the light intensity inside KDP crystal and, therefore, decreases its LIDT.⁸ Chen Mingjun *et al.*⁹ analyze the influences of micro-waviness introduced by the SPDT method on the LIDT of KDP crystal and point out that the most dangerous spatial frequency extent is between $(180\ \mu\text{m})^{-1}$ and $(90\ \mu\text{m})^{-1}$. However, they do not provide some characteristic parameters to describe the machining quality of the KDP surface in order to guide the technical application. Yoshiharu Namba *et al.*¹⁰ use the ultra-precision grinding machine to process KDP crystal and get the conclusion that the LIDT of KDP has a functional relationship with surface roughness; the smaller the roughness, the larger the LIDT. K. C. Robinson *et al.*¹¹ provide an in-process non-destructive measuring method of fused silicon subsurface damage and discuss the correlations of the laser damage and surface roughness. The subsurface quality usually has a certain mapping relationship with the surface quality, and the latter is able to reflect the former to some extent;¹² therefore, the surface quality has fundamental effects on the LIDT of ultra-precision machining optical elements.

The characteristic parameters of surface quality are the basis of establishing the relationship between surface quality and the LIDT, optimizing the machining parameters, and improving the machine architecture. There are lots of characteristic parameters in terms of different surface elements, but not all the parameters have the same meaning when referring to the special function (such as the LIDT), which the optical components must satisfy. For the KDP crystal processed by

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the SPDT method, the micro-waviness and surface roughness have different levels of influence on its LIDT. Finding the chief element that decreases its LIDT furthest and providing suitable characteristic parameters for such an element have critical meaning to improve the LIDT of KDP crystal and guide its ultra-precision machining. In this paper, we study the changing regulation of the LIDT of KDP with some traditional characteristic parameters of surface topography based on the Fourier model method and laser damage experiment in order to find the most suitable parameters to describe the optical quality of the KDP surface.

II. EXPERIMENTAL DESIGN AND TESTING RESULTS

SPDT can directly obtain the surface of sub-micron form accuracy with nano-level roughness without complementary operations, such as lapping or polishing. So it is widely used in processing optical elements with high surface quality. Our experiment is carried out on the special KDP SPDT machine manufactured by Harbin Institute of Technology, and the cutting elementary diagram is shown in Fig. 1. The machine adopts the vertical architecture; the spindle installed on aerostatic bearings is mounted axially to the Z direction, and it has a good rotating accuracy after the dynamic balance adjustment. The slides are fixed on a massive granite block, which rests on four self-leveling pneumatic isolators. A large disk is fixed on the bottom of the principle axis, and the diamond tool is fixed at the edge of the big disk. We divide the KDP sample surface into 18 areas and process each area with different cutting parameters. The current processing course is shown in Fig. 2; the special processing parameters are shown in Table I. Because of the special dynamic structure of the SPDT machine, the change of spindle speed will have some effects on the practical cutting depth, so we carry out our experiment at the same spindle speed in order to ensure the accurate cutting depth. Moreover, all the processing parameters are optimized on the basis of previous lots of experiments, and, therefore, they are more reasonable.

Because of the deliquescence property of KDP crystal, we test the machined surface immediately with an atomic force microscope (AFM) and white light interferometer (WLI). Take the area 1 of group B for example; the 3D topography is shown in Figs. 3(a) and 3(b). The type of AFM is

FIG. 1. (Color online) The machining sketch of SPDT method.

FIG. 2. (Color online) The current processing picture of KDP.

nanoscope produced by American DI company; its sampling area is $80\text{ }\mu\text{m} \times 80\text{ }\mu\text{m}$, sampling period $\Delta = 0.314\text{ }\mu\text{m}/\text{pixel}$, and sampling points are 256×256 . The type and corresponding parameters of WLI is Taylorsurf CCI 2000, $1.76\text{ mm} \times 1.76\text{ mm}$, $\Delta = 3.52\text{ }\mu\text{m}/\text{pixel}$, and 512×512 , respectively.

After the testing of surface topography, we finish the laser damage experiment on every area of the KDP sample by a tri-band Nd:YAG Q-laser of single longitudinal mode, which is able to export the TEM_{00} mode laser with wavelength of 1064 nm stably and effectively. The laser path is shown in Fig. 4, which consists of laser energy adjustment path, laser transmission path, laser focusing path, and high precision platform, except for the laser source. The testing work takes the 1-on-1 mode; there are at least 20 testing points on each area. The dividing of the sample surface, the distribution of testing points, and the testing order are shown in Fig. 5, and the specific experimental parameters are given in Table II.

There are usually three kinds of damage type for KDP crystal based on the experimental observation; they are front surface damage, body damage, and back surface damage, as shown in Figs. 6(a), 6(b), and 6(c), respectively. The damage model is mainly exploding breakage, and the back surface damage is more serious than the front surface. The reason for this phenomenon is the laser self-focusing effect, which makes the laser intensity gradually increase along the light path inside KDP crystal. Because of the newly introduced

TABLE I. Cutting conditions for KDP sample.

Conditions	Group no.		
	A	B	C
Spindle speed (rpm)	400	400	400
Tool plate radius(mm)	315	315	315
Depth of cutting (μm)	10	15	20
Feed ($\mu\text{m}/\text{r}$)	1, 7, 11, 15, 20, 30	1, 7, 11, 15, 20, 30	1, 7, 11, 15, 20, 30
Tool rank angle ($^\circ$)	-45	-45	-45
Tool relief angle ($^\circ$)	18	18	18
Tool nose radius (mm)	5	5	5

FIG. 3. (Color online) 3D topography of KDP surface processed by SPDT method (area 6, group C) (a) detected by AFM and (b) detected by WLI.

defects on the KDP surface by the processing course, such as the absorbing impurities, rupture and the subsurface micro-fracture, the surface will be more easily damaged than the body. Therefore, we consider the surface damage as the damage sign of KDP crystal. We take the mean of the lowest two energy density values that damage the KDP and the largest two energy density values that do not damage the KDP as the LIDT of KDP crystal and consider the standard deviation of them as the error. The experimental LIDT of different areas of the KDP sample are given in Table III.

III. ANALYZING AND DISCUSSING

Reference 9 points out that the micro-waviness on the KDP surface has important influence on its LIDT. Reference 10 gets a conclusion that the LIDT of KDP crystal has a functional relationship with the surface roughness, but this conclusion is based on the ultra-precision grinding, and there is not obvious micro-waviness on the KDP surface obtained by this kind of machining method. For the KDP surface processed by the SPDT method, the micro-waviness and roughness are all significant elements affecting the LIDT. Therefore, we should study in depth the effects of the micro-waviness and roughness on the LIDT of KDP crystal, respectively, and find which one is the leading element. Then, we are able to generalize some characteristic parameters of surface quality, which are not only able to reflect the leading property of the KDP surface, but also work as the sign of LIDT. At last, we can optimize the processing parameters and improve the LIDT of KDP crystal based on these parameters.

A. Detaching of surface frequency information

The AFM is mainly used for getting high frequency information of surface topography, and the WLI is mainly used for obtaining middle frequency and high frequency information.

FIG. 4. (Color online) The laser path sketch of LIDT experiment of KDP crystal.

From Fig. 3(b), we can see that there is obvious periodic waviness on the KDP surface processed by SPDT. However, the original machined surface includes not only the waviness information, but also the roughness information, so it is necessary to detach the roughness information from the original surface firstly. Take the surface shown in Fig. 3(b) for example; based on the Gaussian filtering,^{13,14} the detaching result is shown in Fig. 7. From Figs. 7(a) and 7(b), we can see that the waviness surface, which is mainly introduced by SPDT, is extremely the same with the original surface and that the approximate or average period of waviness is obviously larger than the feed of such an area ($30 \mu\text{m}/r$). The waviness is mainly related to the vibration of the machine elements, such as the spindle axial vibration and the machine body shock excitation. From Fig. 7(c), we can see clearly the tool marks and some mutant peaks, which are mainly introduced by the mutual function of the tool and the workpiece and the random factors during the processing course.

B. Surface waviness and LIDT

Reference 9 considers the micro-waviness with the leading period as the only factor in calculating the relative threshold (RT) of the KDP surface processed by SPDT and provides the most dangerous frequency extent of micro-waviness. However, the factual waviness surface of KDP crystal includes lots of sub-waviness, which all have influence on the LIDT of the KDP sample more or less, and these not-leading frequencies perhaps occupy the largest proportion on the KDP waviness surface. Therefore, we need to find

FIG. 5. (Color online) The distribution of testing points of LIDT experiment of KDP crystal.

TABLE II. The parameters of LIDT experiment of KDP crystal.

Parameters of the laser beam path system					Environmental parameters		
Pulse width /ns	Optical divide ratio	Wavelength λ /nm	Focal area A /mm ²	Incident angle	Vacuum degree	Temperature	Moisture
4.5	1:25	1064	0.3784	0	Atmosphere	20 ~ 23 °C	72%

more reasonable and feasible surface characteristic parameters to study the LIDT of the KDP surface.

After analyzing all the waviness surfaces detached from the processed areas by the power spectrum density (PSD) method,^{15,16} we calculate the amplitudes of all the sub-waviness with characteristic frequency and find that the amplitude extent is below 200 nm and the frequency extent is

below 1000 μm . We still approach the micro-waviness based on the sine wave model and the approximate multilayer structure and calculate the inner light intensity of KDP crystal with the Fourier model method.^{9,17–22} The Fourier model method is a kind of vector electromagnetic field theory which resolves the electromagnetic field of each layer by computing and overlaying each mode field. The P-th layer is

$$\begin{cases} E_y^p = \exp(ik_0\alpha x)W_{ey}^p \{ \exp[ik_0\Gamma_+^p(z-z^p)]u^p + \exp[ik_0\Gamma_-^p(z-z^p)]d^p \} \\ \sigma H_x^p = \exp(ik_0\alpha x)(-W_{hx}^p) \{ \exp[ik_0\Gamma_+^p(z-z^p)]u^p - \exp[ik_0\Gamma_-^p(z-z^p)]d^p \}, \end{cases} \quad (1)$$

where E is electric intensity; H is magnetic induction; σ is conductivity; k_0 is wave vector; W_{ey} and W_{hx} are the electric field eigenvector matrix and magnetic field eigenvector matrix, respectively; Γ_+ , Γ_- are the up-going wave eigenvalue matrix with positive eigenvalues and downlink wave eigenvalue matrix with negative eigenvalues, respectively; u^p and d^p are two column vectors composed of eigen-mode field amplitude coefficient of up-going wave and downlink wave, respectively; and x , y , and z are the coordinates.

Light intensity can be obtained by the following equation:

$$I = \frac{1}{2} |\text{Re}(\mathbf{E} \times \mathbf{H}^*)|. \quad (2)$$

Define the light intensity modulation degree

$$M_I = I_{\max}/I_{\text{pref}}, \quad (3)$$

where I_{pref} is the light intensity inside KDP crystal under the ideal situation (without the micro-waviness) and $I_{\max}$ is the light intensity maximum inside KDP crystal modulated by

micro-waviness. Modulation degree M_I is defined as the sign of the failure chance of ICF system optical elements; namely, the bigger the modulation degree, the more easily the optics are destroyed by the laser.

Figure 8 shows the relationship of modulation degree and different frequencies. From Fig. 8, we can see that the modulation degree changes not very observably with the frequencies within the most dangerous frequency extent between $(180 \mu\text{m})^{-1}$ and $(90 \mu\text{m})^{-1}$, which is concluded in Ref. 9, but increases nearly linearly with the amplitude, and the range is larger than that induced by frequency. Therefore, we should consider the amplitude information of waviness as the most important element when we try to find characteristic parameters of surface quality to judge the LIDT of the KDP surface machined by the SPDT.

Because the waviness surface consists of lots of sub-waviness with different amplitudes, so we need a parameter which is able to reflect the average value of waviness fluctuating. Arithmetical mean deviation of three-dimensional profile S_a and root mean square deviation of three-dimensional contour S_q are able to satisfy this requirement well. They are defined as follows, respectively:

FIG. 6. (Color online) Damage points morphology of KDP crystal: (a) the front surface damage; (b) the body damage; and (c) the back surface damage.

TABLE III. The experimental value of LIDT of KDP crystal (J/cm^2).

Area no.	Group no.		
	A	B	C
1	12.78 ± 0.95	13.40 ± 1.00	12.26 ± 0.71
2	14.63 ± 0.60	12.45 ± 1.01	8.63 ± 0.49
3	14.65 ± 0.44	11.97 ± 0.47	8.50 ± 0.37
4	15.64 ± 0.93	12.18 ± 0.41	8.01 ± 0.62
5	15.10 ± 0.40	11.46 ± 0.51	9.44 ± 0.64
6	16.33 ± 0.81	12.08 ± 0.56	9.02 ± 0.69

$$S_a = \frac{1}{MN} \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} |Z(x_m, y_n) - \mu|, \quad (4)$$

$$S_q = \sqrt{\frac{1}{MN} \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} [Z(x_m, y_n) - \mu]^2}, \quad (5)$$

where M , N are the number of sampling points along the x direction and the y direction, respectively; $Z(x_k, y_l)$ is the sampling height value; and nominal height is

$$\mu = \frac{1}{MN} \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} Z(x_m, y_n)$$

We calculate the S_a , S_q of the waviness surface and original surface and compare their changing regulations with the experimental LIDT. Figure 9 shows the changing regulations of the reciprocal of S_a or S_q with different feeds, and Fig. 10 shows the changing trends of experimental LIDT. From Fig. 9, we can see that the changing trends of the reciprocal of S_a or S_q are different under different cutting depths, because of the different vibration situation of the machine with special cutting depth. When cutting depth $ap = 10 \mu\text{m}$, the reciprocal of S_a or S_q tends to increase with the increasing feed, but the bigger cutting depths tend to make their values decrease with the increasing feed, and under the same cutting depth, the average value of the reciprocal of S_a or S_q of all the six machined areas decrease with the increasing feed. In addition, the changing regulation of S_a (or S_q) of the waviness surface and that of the original surface are the same under the same cutting depth, although the special values have some differences, which are mainly caused by the detaching of roughness information from the original machined surface. So we can even directly calcu-

FIG. 8. (Color online) Modulation property curve of micro-waviness period.

late the S_a or S_q of the original surface instead of detaching the waviness surface when the waviness is obvious enough on one surface, like the KDP surface processed by SPDT. From Fig. 10, we can see that the changing regulation of experimental LIDT is nearly the same with that of the reciprocal of S_a or S_q under the given cutting depth, just as shown in Fig. 9. Furthermore, from Fig. 9(b) and Fig. 10(b), we can clearly see that the experimental LIDT points and the reciprocal of S_a or S_q points almost have the corresponding relationship between one and one within the extent of experimental errors. So we can conclude that the LIDT has an inverse function relationship with surface S_a or S_q , and the smaller surface S_a (or S_q) means the larger surface LIDT.

Based on the analysis above, we can forecast the LIDT of the KDP surface machined by the SPDT by testing directly the S_a or S_q of the original surface. Here, we need to notice that the original surface includes lots of sub-waviness information, and we should use the testing equipments which have enough sampling area and sampling points. For example, the sampling area of AFM is $80 \mu\text{m} \times 80 \mu\text{m}$, which is not able to include the dangerous frequency extent between $(180 \mu\text{m})^{-1}$ and $(90 \mu\text{m})^{-1}$; so the topography data obtained by AFM is not suitable for calculating the characteristic parameters S_a and S_q .

C. Surface roughness and LIDT

The surface roughness is not able to be avoided with any mechanical processing method, and it will affect the using properties of components, especially the optical elements. The theoretical roughness is only related to the circular

FIG. 7. (Color online) The detaching of original surface topography: (a) original surface; (b) waviness surface; and (c) roughness surface.

FIG. 9. (Color online) The reciprocal of Sa or Sq on each area curve with different feeds: (a) $ap = 10 \mu\text{m}$; (b) $ap = 15 \mu\text{m}$; and (c) $ap = 20 \mu\text{m}$.

radius of the tool tip and the feed;^{23–25} based on the cutting theory, we can know the theoretical surface roughness R_a as follows:

$$R_a = f^2 / (8\pi \times r) \times \cos(45^\circ), \quad (6)$$

where f is the feed per rotation, $\mu\text{m}/\text{r}$, and r is the circular radius of the tool tip, μm .

The roughness on the KDP surface affects the focusing quality of the outgoing laser beam by scattering and has also certain influence on the LIDT more or less by enhancing the heat absorbing. However, there is lots of micro-waviness on the KDP surface machined by the SPDT, and this micro-waviness will seriously modulate the incident laser intensity. We observe the laser-induced destroying course of KDP crystal and find the filamentous destroying path inside KDP crystal, which is caused by a small scale focusing effect induced by micro-waviness. Therefore, we can know that the modulation effect of micro-waviness has larger influence on the LIDT of KDP crystal than the absorbing and scattering effects of surface roughness. Furthermore, we can guess that the roughness value has no corresponding relationship with the LIDT.

Figure 11 shows the changing regulation of roughness with different feeds; we can see that the roughness increases with the increasing feeds under different cutting depths,

which is corresponding with the function relationship given in Eq. (6), and the cutting depth has no obvious influence on roughness. Comparing Figs. 11(a) with 11(b), we can know that the roughness data detached from the original machined surface (tested by the WLI) is nearly the same with the data obtained by AFM, which illustrates that the detaching method we used is correct. Figure 11 and Fig. 10(a) tell us that the changing trends of roughness with different feeds are the same with that of LIDT when the cutting depth ap is $10 \mu\text{m}$, namely, that the bigger the roughness, the larger the LIDT, which is obviously not fitting with the practical condition. This phenomenon confirms our guess above, and the only explanation is that the influence of waviness on the LIDT takes up the leading role, rather than that of roughness on the KDP surface processed by the SPDT.

Based on analyzing the above, we can conclude that the arithmetical mean deviation of three-dimensional profile S_a and root mean square deviation of three-dimensional contour S_q obtained by suitable testing equipment are able to be considered as characteristic parameters of surface optical quality for KDP crystal machined by the SPDT method in order to predict the LIDT of the KDP element. In addition, the smaller feed and cutting depth tend to produce smaller S_a or S_q , thereby improving the LIDT of KDP. Meanwhile, we also should find out all the factors that introduce the middle frequency micro-waviness and control them effectively, and

FIG. 10. (Color online) The experimental LIDT curve with different feeds: (a) $ap = 10 \mu\text{m}$; (b) $ap = 15 \mu\text{m}$; and (c) $ap = 20 \mu\text{m}$.

FIG. 11. (Color online) The roughness curve with different feeds: (a) the testing result of AFM and (b) the testing result of WLI.

decrease the amplitude of waviness as much as we can. Then, we can obtain the ideal LIDT of KDP crystal, which is able to satisfy the requirement of ICF.

IV. CONCLUSIONS

In this paper, based on the Fourier model theory and LIDT experiment, we study the relationship between relevant characteristic parameters of surface topography and the experimental LIDT. The theoretical and experimental results show that:

- (1) The waviness is the leading property on the KDP surface machined by the SPDT method when the LIDT is considered; we should firstly choose suitable surface topography testing equipment with enough sampling points and sampling area, which is able to include the complete waviness information on KDP surface, such as the WLI, rather than the AFM.
- (2) The amplitude of micro-waviness has more serious influence on the light intensity inside KDP crystal within the dangerous frequency scope between $(180\mu\text{m})^{-1}$ and $(90\mu\text{m})^{-1}$; the light intensity modulation degree increases nearly linearly with the amplitude of waviness.
- (3) The characteristic parameters of waviness amplitude, such as the arithmetical mean deviation of three-dimensional profile S_a or root mean square deviation of three-dimensional contour S_q , are able to be considered as characteristic parameters of surface optical quality in order to judge approximately the LIDT of the KDP surface.
- (4) The smaller feed and cutting depth tend to produce smaller S_a or S_q and thus improve the LIDT of KDP, and we should do our best to find out all the factors that introduce the middle frequency waviness, control them effectively, and decrease the amplitude of waviness, so then we can improve the LIDT of KDP crystal.

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