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ORIGINAL ARTICLE

A finite element analysis of sawing stress in fixed-abrasive wire saw slicing KDP crystal

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Abstract Potassium dihydrogen phosphate (KDP) crystal is the preferred nonlinear optical crystal used in pockels cell and frequency multiplier. Slicing machining is the first process for KDP crystal, which has an important effect on the yield rate. However, KDP crystal is easy to crack when sliced due to the maximum tensile stress. This paper presents the finite element analysis of sawing stress in fixed-abrasive wire saw slicing KDP crystal. The finite element model of wire sawing KDP crystal is found, and the sawing forces are analyzed and loaded to the cutting kerf that are simplified as the normal sawing pressure *p* contrary to the workpiece feed direction and the tangential sawing pressure *q* along the wire moving direction, based on the analysis of fixed-abrasive wire saw cutting mechanism. The dynamic distribution and variation rule of the sawing stress and the coupling of sawing stress with crystal initial internal stress have been analyzed when slicing the (001) crystal plane optical device, and the critical initial internal stress of the KDP crystal to avoid cracking in wire saw cutting is discussed. Numerical simulation results show that the sawing stress for cutting KDP crystal without initial internal stress is a low-stress machining way, but a larger tensile stress produces due to the initial stress gathering in the kerf coupled with the low sawing stress. A greater crystal initial internal stress can lead to the more intense concentration of sawing stress; it suggests that the initial internal stress inside the sawed KDP crystal should be less than 2.294 MPa. The research results help to further understand the sawing stress field distribution and change in the process of slicing KDP crystal.

Keywords KDP crystal · Fixed-abrasive wire saw · Sawing stress · Finite element analysis

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1 Introduction

Potassium dihydrogen phosphate (KH_2PO_4, KDP) which has a high nonlinear coefficient and laser damage threshold is currently the only optical crystal material used in pockels cell and frequency multiplier of the inertial confinement fusion (ICF) program [1]. However, potassium dihydrogen phosphate (KDP) crystal is easy to crack in the process of crystal growth, being taken out from crystallizer and slicing, with the characteristics of low hardness, high brittleness, easy deliquescence and temperature-sensitive, and so on [2–4]. So far, a lot of studies have been mainly focusing on the KDP crystal ultra-precision machining after slicing [1, 5–8]. As the first machining process of KDP crystal, the slicing process directly influences the yield rate and the subsequent processing. Currently, the additional stress can easily lead to a large-size KDP crystal cracking when using the fixed-abrasive band saw for slicing [9]. And the laser separating technology has not yet been formally applied to actual slicing of large KDP crystal with a complex initial internal stress distribution [3, 4].

To date, many studies reveal that the fixed abrasive wire saw slicing technology with the advantages of tiny kerf loss, lowing sawing stress, and ability to slice large-size crystals [10–14] is a relatively ideal processing technology for slicing KDP crystal. The fixed abrasive wire saw technology for slicing KDP crystal is currently still in research stage. The free abrasive wire saw slicing technology [15], using a loose abrasive slurry and bare wire, cannot be used for KDP crystal machining because of the characteristic of low hardness of KDP crystal, so the machining particles can embed in the crystal sliced surface easily that can further increase the subsurface damage depth of sliced KDP crystal. The fixed-abrasive wire saw is made by the way of fixing the diamond grits on surface of a high-strength metal wire adopting methods of composite electroplating and resin-bonded. And through analyzing the machined surface of KDP crystal sawed by using the fixed-abrasive wire saw, the results show the surface defects consist of some obvious serrated form grooves, lots of brittle fracture or brittle crash, intermittent scratch marks, orange peel appearance, embedded abrasive, and some pits [16]. The research results show the lower subsurface damage depth (SSD) can be obtained when adopting the wire saw slicing technology via comparing machining experiments using the fixed-abrasive wire saw and band saw. Therefore, the fixed-abrasive wire sawing technology shows a good applicability in KDP crystal sawing experiment, which can achieve the low stress slicing of crystal materials.

At present, the cracking of KDP crystal in the process of slicing has become a bottleneck problem to be solved. The maximum tensile stress is considered as the main reason for the cracking of crystal in the machining process [17–19]. So far, it is difficult to effectively study and verify the internal stress variation of KDP crystal in the sawing process, due to the real-time measurement of internal stress of KDP crystal is a difficulty experimental work. Usually, the penetration depth of the common nondestructive measurement is small which means the stress dynamic distribution inside the KDP crystal cannot be measured accurately. In view of the requirement of KDP crystal slicing process, in order to better understand the stress field distribution change in wire saw slicing KDP crystal, the stress field variation rule of KDP crystal and the coupling of sawing stress with initial stress inside the crystal in fixed abrasive wire sawing process has been analyzed by employing the finite element method in this paper. The research results are helpful to further understand the distribution and change of sawing stress field in the slicing process and analyze of the crystal cracking mechanism that can provide an important theoretical value for understanding and development of precision slicing technology of KDP crystal.

2 Sawing force analysis of fixed abrasive wire slicing

2.1 Fixed abrasive diamond wire saw slicing principle

The machining principle of reciprocating fixed abrasive wire saw slicing large diameter KDP crystal is shown in Fig. 1. The wire tensioned on the guide pulley moves along the Y direction as a set speed driven by the wire saw spool, and the KDP crystal clamped on the working table feeds along the X direction perpendicularly to the direction of the wire movement as a certain speed or pressure. The coolant liquid is poured to the cutting area through the nozzle to achieve cooling and cleaning effect. Compared to the diamond band saw cutting, the additional force acting on the crystal caused by vibration and deformation of wire in the slicing process is very small, the main reason is the wire section is circular, and the diameter is less than 0.5 mm with characteristics of low stiffness and prone to elastic deformation. So the wire sawing process has features of stable and low machining stress. At present, a reciprocating wire saw machine developed by our research group can achieve KDP crystal sawing experiments, with features of stepless-adjusted wire speed and tension force in a certain range.

2.2 Sawing force analysis

Figure 2 shows the force model in cutting of KDP crystals. The wire is curving in the cutting process under the action of the normal sawing force, and the tension force on each point of the wire is different due to the action of the tangential sawing force. The contact area of the wire and crystal in the sawing process is simplified as the point contact, and the force diagrammatic sketch is seen in Fig. 2b. Where F_N is simplified as the concentrated normal sawing force loading to the wire, and F_T is the total tangential sawing force; F_a is the wire tension force in the wire entry direction at the location of the wire-guide pulley, and F_b is the wire tension force in the wire movement direction at the location of another wire-guide pulley; w_a and w_b are the deflections of the wire at the cut entry point and the cut out point of the workpiece, respectively. And α and β are the wire bow angles that can be measured by the goniometer or calculated by measuring the distance L_s between the two wire-guide pulleys, the workpiece length L, the wire deflections w_a and w_b. The normal and tangential sawing pressures on the unit contact area of the wire are denoted by p and q, respectively.

As shown in Fig. 2b, the balance of forces at the contact point can be expressed as:

$$\begin{cases} F_N = F_a \sin\alpha + F_b \sin\beta \\ F_T = -F_a \cos\alpha + F_b \cos\beta \end{cases} \quad (1)$$

The wire tension forces of F_a and F_b acting in opposite directions can be measured by the tension detection system of the wire saw machine tool, and the wire bow angles α and β also can be obtained. Therefore, the normal and tangential sawing forces F_N and F_T loading on the wire can be calculated by using Eq. (1). Based on the principle of acting force and reacting force, the sawing forces acting to the workpiece and the wire have the same values and the opposite directions.

During the process of wire sawing, the grits in different positions of the wire cross section have different cutting thickness and sawing force, due to that, the size and protrusion

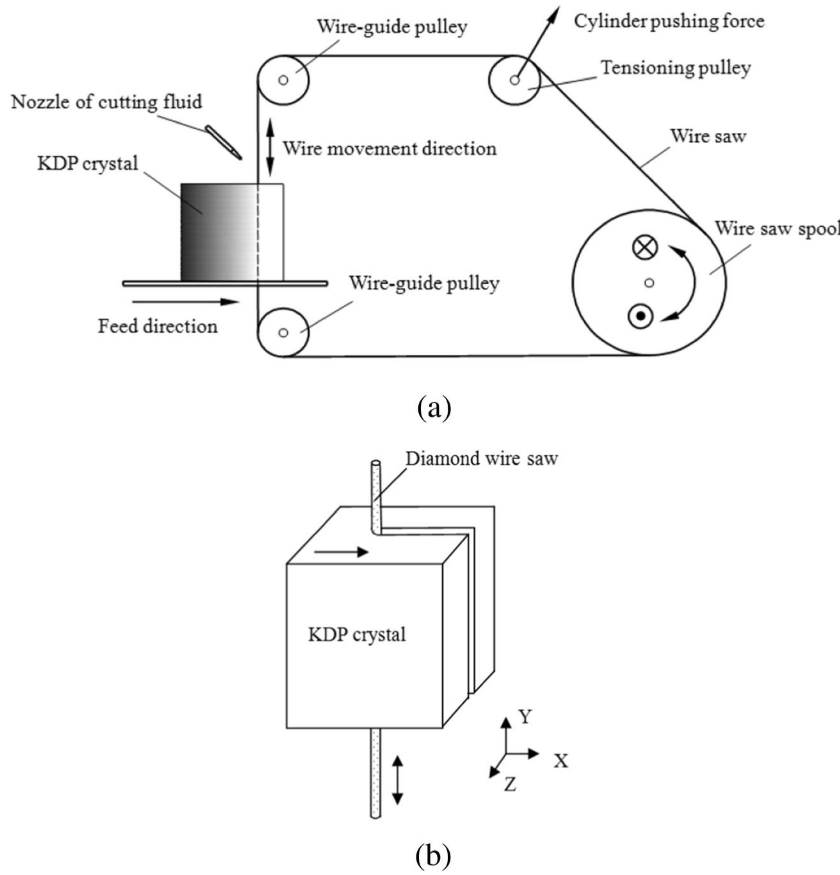


Fig. 1 Schematic of reciprocating wire saw slicing KDP crystal: **a** schematic diagram of machine tool and **b** sketch of the sawing process

height of the abrasives on the wire surface are not the same. Therefore, it's difficult to load the normal and tangential sawing forces of every single grit with different positions on wire surface to the crystal when analyzing the crystal subjected to the sawing forces, so the analysis of the process of the crystal subjected to the sawing forces is simplified. Assuming that kerf width of the wire saw cutting is d, through the process of simplification and equivalent, the total normal sawing force and tangential sawing force can be transformed into the normal sawing pressure p on unit contact area in the opposite direction of the crystal feed and the tangential sawing shear q along the direction of the wire saw movement, respectively, which can be expressed as:

$$\begin{cases} p = F_N/Ld \\ q = F_T/Ld \end{cases} \quad (2)$$

3 Finite element model of wire sawing KDP crystal

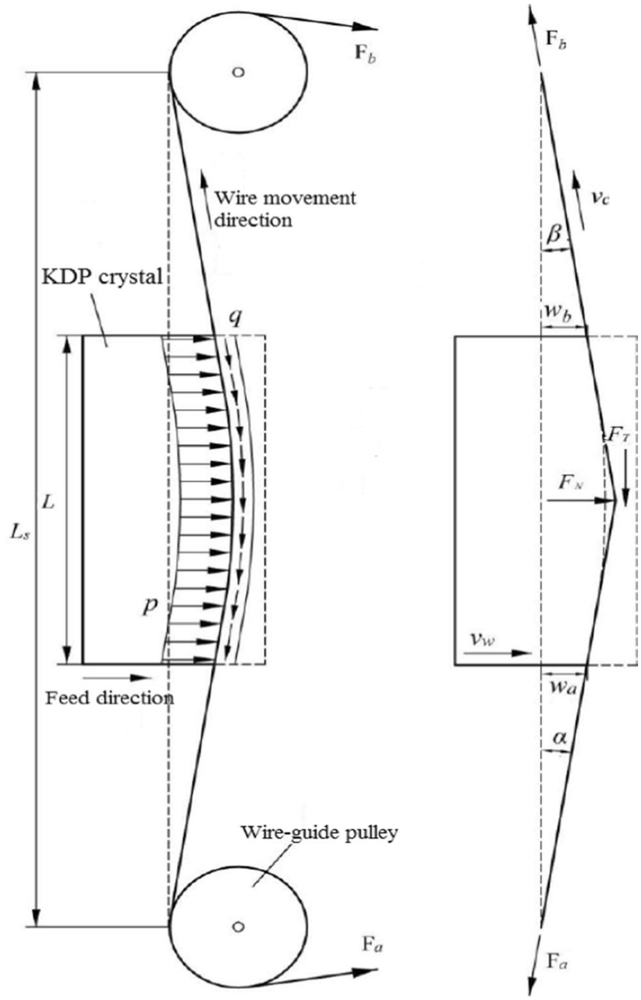
3.1 Process of simulation analysis

According to the fixed abrasive wire saw slicing principle, the finite element analysis model (FEM) of wire saw machining KDP crystal was established by using ABAQUS software, and the sawing stress distribution was analyzed based on ABAQUS/standard implicit algorithm. The finite element simulation process of wire saw cutting KDP crystal is shown as Fig. 3. A three-dimensional geometric model of the KDP crystal is created by using ABAQUS/CAE, then the material parameters of the KDP crystal are defined, and the analysis steps and boundary condition are set up by considering the actual machining process. Next, the sawing forces are loaded dynamically to the crystal model, and the initial stress filed is introduced to analyze the coupling effect with the sawing forces. At last, the simulation results are discussed and analyzed.

Considering the difficulty and effectiveness of simulation modeling and calculation, the FEM was established with the following reasonable simplification and hypothesis made such as ignoring the wire saw flexibility and vibration effects, ignoring the influence of temperature rise on the crystal stress field considering the good cooling condition in the sawing process, and assuming that the sawing trajectory was a straight line and the sawing forces acting on the crystal sawed surface were uniform.

3.2 Finite element model and boundary conditions

In the simulation analysis of the paper, the crystal size was adopted with length × width × height as 100 mm × 100 mm × 100 mm; the sawed slice thickness



(a) (b)

Fig. 2 Sketch of the force model in cutting of KDP crystals: **a** actual curving of wire and **b** simplified force model of wire

was 15 mm and the kerf width was 0.4 mm. The (001) crystal plane was chosen as the sawed surface, and the crystal feed direction was along the [100] crystal orientation as well as the wire movement direction was along the [010] crystal orientation. The three-dimensional geometric model and finite element model of KDP crystal sliced by wire saw are shown in Fig. 4. The KDP crystal bottom (010) crystal plane is fixed on the feed table in wire cutting, so the surface OTUR in the model is fixed, seen in Fig. 4.

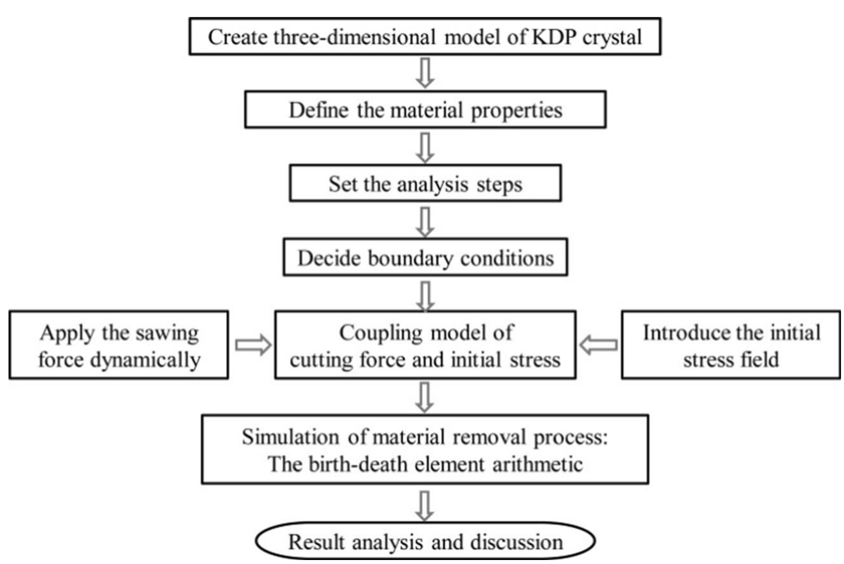
The eight-node linear hexahedral element C3D8I was chosen for meshing model, and the finer meshing was adopted in the kerf and its adjacent area. Further, the FEM used in this paper has been selected and verified by comprehensively considering the calculation accuracy and efficiency. The mesh independence is verified by changing the mesh size with mesh numbers 33,390, 54,019, 75,264, and 94,441. The analysis results show the calculation deviation are less than 2% when adopting the mesh numbers of 75,264 compared with mesh numbers of 94,441, but the calculation time is greatly reduced, which means the FEM used in this paper with mesh numbers of 75,264 is appropriate.

KDP crystal is a typical anisotropic elastic-brittle material at room temperature, and the material parameters of KDP crystal are shown in Table 1 [20].

3.3 Initial internal stress field

There is a dynamic distribution of stress field in the process of wire saw slicing KDP crystal, wire saw machining causes release and redistribution of the initial internal stress inside the crystal, which is coupled to sawing stress in the slicing process. It is difficult to obtain the accurate distribution of the initial stress field inside the crystal since the initial stress is influenced by the crystal growth, the process of taking out from the crystallizer and annealing even the movement, and

Fig. 3 Finite element simulation process of wire saw cutting KDP crystal



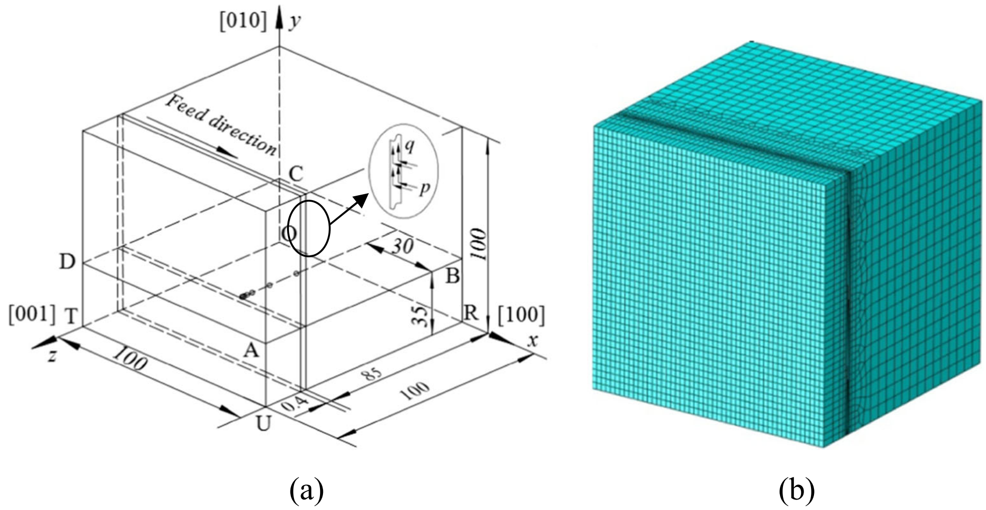


Fig. 4 Model of wire saw cutting KDP crystal: **a** three-dimensional geometric model and **b** finite element model

there still exist some restrictions and difficulties on the experimental methods to test the macro internal stress of crystal. Based on the above problems, the internal stress field of the crystal after being taken out from the crystallizer and cooling (the temperature gradually decreases from 323 to 298 K) was used as the initial stress field in this paper for the simulation process, then the initial stress field was applied to the finite element model as the initial condition. Meanwhile, the sawing stress field caused only by the machining force and gravity without the initial stress was also analyzed in order to study the distribution regularity of sawing stress.

3.4 Loading the sawing force and simulation of material removal process

There is no wire appearing in the simulation process because of the complexity of tool machining motion in wire sawing. Instead, only the sawing forces were loaded to the finite element model equivalently, and the simulation of the sawing force moving along the material removal direction was finished through the setting of the dynamic load-step. The material removal process was realized by using the birth-death element arithmetic of ABAQUS finite element software, which means the material removal is represented as an element to be "killed" when the saw force applies on it. In the simulation calculation process, the node force of "the being killed element" is set to zero and does not participate in the subsequent calculation. At the same time, "the being killed elements" are not displayed in the post-processing of the simulation results, so as to realize the simulation of the material removal process.

The sawing forces of the KDP crystal applied include the normal sawing force opposite to the direction of the crystal feed and the tangential sawing force along the direction of the wire movement. The research results of orthogonal experiment on the analysis of processing parameters of KDP crystal wire saw cutting show that the better machined surface quality is obtained when the wire speed is 1.5 m/s and the crystal feed rate is 10 μm/s [13]. Therefore, the above set of parameters combination was selected for the finite element analysis.

The normal sawing pressure p and tangential sawing shear q on unit contact area, which were loaded on the whole narrow kerf surface (with width × length is 0.4 mm × 100 mm, as shown in Fig. 4), were calculated by using the experimental measuring results and the Eqs. (1) and (2).

4 Results and discussion

4.1 Initial internal stress field

Figure 5 shows the initial internal stress field distribution of (001) crystal plane (ABCD plane as shown in Fig. 4), which is approximate uniform distribution in the depth direction (along the y direction). The maximum initial internal stress occurs at the center of the crystal, which is 1.093 MPa. From the inside of the crystal to the outside, the initial stress value is gradually reduced.

Table 1 Material parameters of the KDP crystal

Density/kg m^{-3}	Compliance S_{ij}/GPa^{-1}						Thermal expansion /10^{-6} K^{-1}		
ρ	s_{11}	s_{12}	s_{13}	s_{33}	s_{44}	s_{66}	α_1	α_2	α_3
2338	0.0151	0.0018	−0.004	0.0195	0.0781	0.162	16	16	29

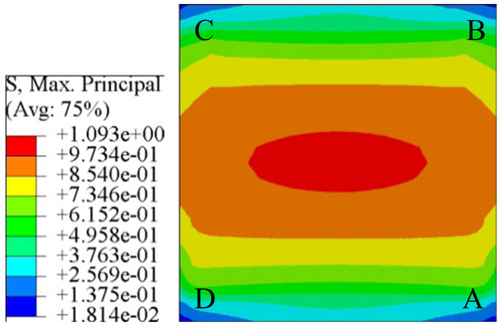


Fig. 5 Initial internal stress distribution of the crystal plane ABCD

4.2 Stress at the sawing kerf

The numerical results show the sawing stress of the crystal without the initial internal stress is only about 0.1–0.2 MPa. In the process of wire sawing KDP crystal, the sawing stress and initial internal stress inside the crystal couple mutually at the sawing kerf and the sawing kerf area usually has the maximum stress in the crystal. Figure 6 shows the first principal stress distribution on the crystal cross section ABCD at a stable sawing stage in the sawing feed depth of 50 mm of crystal including the initial internal stress, and the maximum tensile stress at the sawing kerf is 2.863 MPa. In contrast to Fig. 5, the maximum initial stress of crystal before processed is only 1.093 MPa, which means that the initial stress is concentrated at the kerf in the sawing process. This reveals that the probability of crystal cracking increases during the wire saw slicing process when the crystal initial internal stress becomes larger which causes more obvious stress concentration around the sawing kerf.

4.3 Dynamic changes of the maximum tensile stress in the crystal sawing process

KDP crystal with the material characteristics of low hardness and high brittleness is easy to crack under tensile stress, therefore, the maximum tension stress theory is used as the main factor to judge whether the crystal cracking in the wire sawing process.

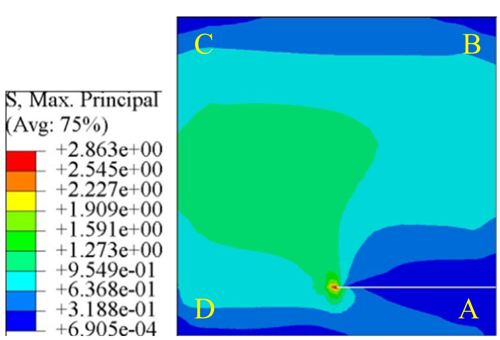


Fig. 6 Sawing stress distribution during stable cutting stage

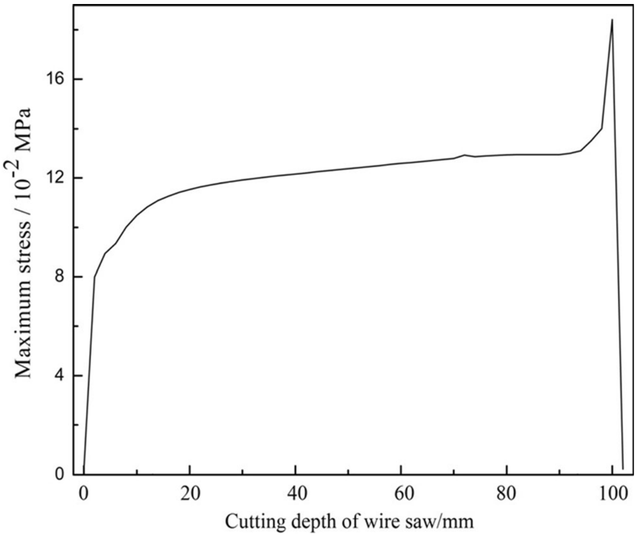


Fig. 7 Maximum stress variation with cutting depth without the crystal initial stress

Figure 7 shows the dynamic variation of the maximum tensile stress of the crystal with the cutting depth which is from the beginning of the wire saw contacting with the workpiece until the completion of the sawing process to form a slice, only under the action of the sawing stress field without the initial stress of the crystal. The simulation results show that the sawing stress is lower with the value at about 0.1–0.2 MPa which belongs to a low-stress machining way, because the material removal in the wire sawing process is achieved by the scratching interaction of the diamond grits on the wire saw surface. And Fig. 8 shows the variation of the maximum internal tensile stress with cutting depth change under the coupling effects of the sawing stress field and the initial internal stress inside the crystal. The simulation results show that there is stress accumulating and concentration of original initial

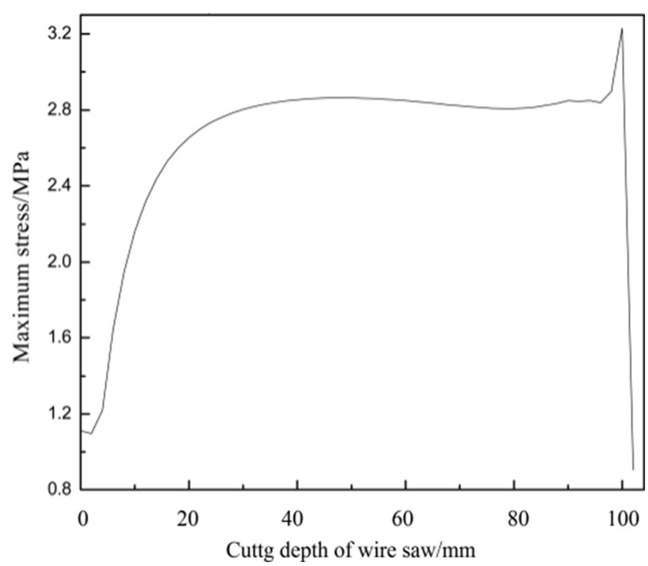


Fig. 8 Maximum stress variation with cutting depth in coupling stress condition

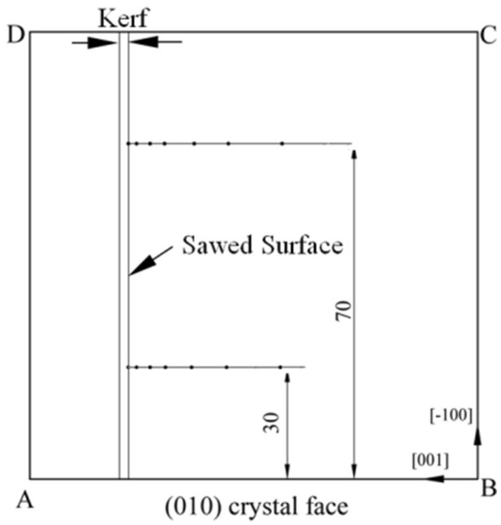


Fig. 9 Sketch of choosing the stress calculation points

internal stress at the sawing kerf when the sawing stress field, and the crystal initial stress couple mutually in the wire sawing process, resulting in the maximum stress at the crystal sawing kerf from 1.1 MPa increasing to 3.2 MPa. This shows that the stress concentration caused by the redistribution of initial internal stress in the sawing process is a possible major reason for the cracking of KDP crystal.

The variation of the maximum internal tensile stress of the crystal in the wire sawing process with the machining time can be divided into three stages: initial sawing stage, stable sawing stage, and cutting off stage (as shown in Figs. 7 and 8). In the initial sawing stage, the time of the wire sawing into the crystal is not long, and the initial stress in the crystal accumulates slowly at the sawing kerf, then the maximum stress increases gradually from a lower value before processed to a steady state. After entering the stable sawing stage, the maximum stress remains steady which is due to the dynamic balance of the concentration of internal stress at the sawing kerf and the stress relief caused by the material removal in the machining process. When the KDP crystal is about to be cut off, the stress fluctuation significantly becomes large, and the stress value transiently increases to the maximum since the stress concentrates on the remaining crystalline material, which increases the risk of crystals cracking. When the crystal is sawed into two pieces after the sawing process is finished, the maximum stress of the crystal recovers to an approximate value as before processed. By in comparison to Figs. 7 and 8, it shows that the time for getting to the stable sawing stage is longer due to the influence of the redistribution of the initial stress field.

4.4 Dynamic distribution of stress field

Under the action of sawing stress and material removal, the stress field in the crystal changes dynamically. To study the variation rule of the crystal internal stress in the process of wire sawing relative to its initial internal stress, the stress of the points on the plane ABCD, as seen in Fig. 4, with the distances to the sawed surface are 0, 0.5, 1, 2.5, 5, 15, and 30 mm, and the wire sawing depths are 30 and 70 mm, respectively, are selected to analyze, as shown in Fig. 9.

The stress change rate K is selected to characterize the magnitude of stress change in each point inside the crystal,

$$K = \sigma_t / \sigma_0 \tag{3}$$

where σ_t is the stress of the test points at a certain moment in the processing, and σ_0 is the initial internal stress of the corresponding points. The K values of each test point with time changes are shown in Fig. 10.

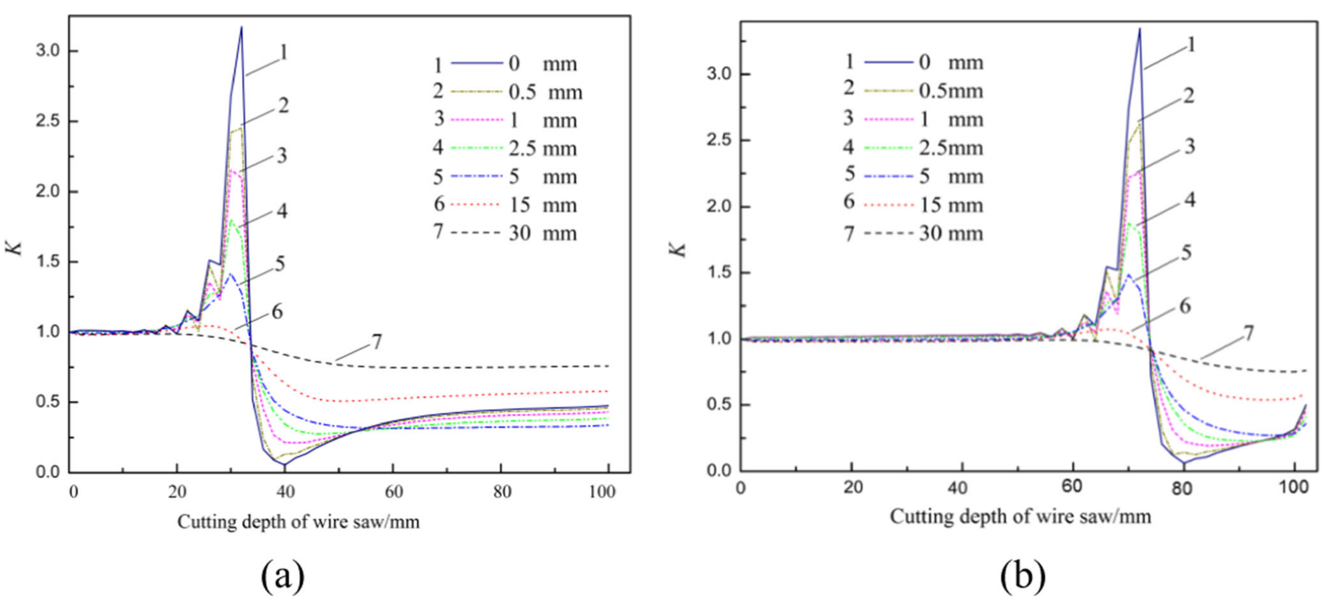


Fig. 10 Change rates of crystal stress for test points with the wire sawing process: **a** the sawing depth is 30 mm and **b** sawing depth is 70 mm

The kerf becomes deeper with the KDP crystalline material is removed in the sawing process, the stress around the sawed area increases rapidly when the wire is approaching. As shown in Fig. 10, the stress value of each point reaches the maximum while the wire is getting to the desired sawing depth of 30 and 70 mm. After the wire cut, the new crystal surface is formed and the strain energy releases with the removal of material, and the crystal internal stress relative to its initial internal stress reduces greatly accompanying with the release of the initial stress of the crystal in the sawing process. The stress change rates of the points which are far away from the newly formed crystal surface in the sawing process are small and will gradually increase when closing to the cutting area with the increase of the initial internal stress release. The change rates of crystal stress for test points with the different sawing depth of 30 and 70 mm show similar changing characteristics; these two positions have the same distance to the center of the crystal with the maximum initial internal stress.

4.5 The safety range of the initial internal stress of KDP crystal for slicing

The preceding analysis results show that the stress concentration will occur around the kerf in the wire saw cutting process, and will increase significantly especially when the wafer is going to be cut off. And the greater residual stress can result in the higher concentration of the maximum stress around the kerf. Therefore, in order to ensure that the KDP crystal does not appear cracking in the cutting process, it is necessary to reduce the crystal internal stress by annealing. By changing the initial stress field strength, the change rule of the maximum coupled stress value in the stable cutting process is obtained with the change of the maximum initial internal stress in the crystal, as shown in Fig. 11. The least square method is used to fit the relationship between them, and it is found that the variation is a linear rule expressed as follow:

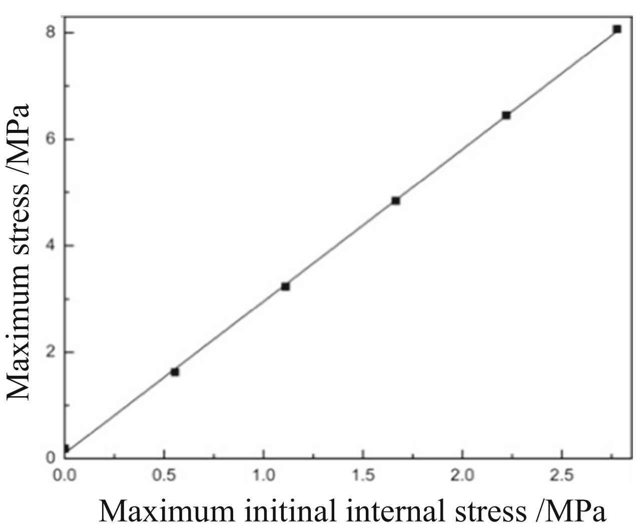


Fig. 11 Relationship between the maximum stress and the maximum initial internal stress

$$f(x) = 2.856x + 0.118 \quad (4)$$

where $f(x)$ is the maximum tensile stress in the stable process of wire sawing KDP crystal, and x is the maximum initial internal stress inside the crystal.

The KDP crystal mechanic characteristics test found that the critical stress of crack propagation is 6.67 MPa [21], so making $f(x) = 6.67$, the x value can be got by using Eq. (4). It is concluded that the critical initial internal stress of the KDP crystal to avoid cracking in wire saw cutting is 2.294 MPa when adapting the cutting parameters in this paper. In other words, when the initial internal stress inside the sawed KDP crystal is less than 2.294 MPa, the crystal can be cutting by wire saw without cracking.

5 Conclusions

In this paper, based on the analysis of fixed abrasive wire sawing cutting principle and mechanical analysis, the variation rule of the wire sawing stress has been analyzed by taking the sawing process of (001) crystal plane as an example. This study gets the following conclusions:

(1) The simulation results show that the sawing stress value is about 0.1–0.2 MPa only under the action of the sawing force without the initial stress inside the crystal. It reveals that the fixed abrasive wire sawing brings a low cutting stress for the machining of soft-brittle KDP crystal. When the KDP crystal is about to be cut off, the stress fluctuation significantly becomes large, and the stress value transiently increases to the maximum, which increases the probability of crystal cracking.

(2) There is a complex internal stress inside the KDP crystal with the redistribution of the crystal initial internal stress in the sawing process. And the crystal stress change rate is greater in the sawing process when the distance to the processing zone is closer; similarly, the crystal stress change rate is smaller when the distance is farther due to the impact of the initial stress that becomes smaller.

(3) During the wire sawing process, there is a dynamic coupling of the sawing stress with the initial internal stress which makes the crystal internal stress concentrated at the sawing kerf. And the greater the crystal initial internal stress is, the more intense the stress concentration is, which means that the probability of KDP crystal cracking increases. In order to ensure that there is no cracking in the wire cutting KDP crystal, it suggests that the initial internal stress inside the sawed KDP crystal should be

less than 2.294 MPa when adapting the cutting parameters in this paper.

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