

PING-PONG FIXED ABRASIVE DIAMOND WIRE SAW SLICING PIEZOELECTRIC CRYSTAL QUARTZ

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Abstract. Fixed abrasive diamond wire saw is widely used for slicing crystal quartz to manufacture new piezoelectric dynamometers. However, the process has always the problem of slicing out-of-straight influencing the dynamometer's indicators, the optimization methods of machining and slicing process are studied in the paper. Developments of fixed abrasive diamond wire machining are reviewed firstly. A research system is built to monitor process and measure cutting forces. The 3-axis forces and their relationship with tension-force are investigated by measured curve. Force analysis of diamond wire at changing direction is shown in the experiment and the rule of slicing straight is found. Finally, suggestions on slicing parameters and methods are put forward.

1. Introduction

Piezoelectric dynamometers are generally used in the fields such as precision machining and force measuring [1]. The dynamometers, as integration form, are manufactured by a few companies, e.g. Kistler, PCB. In special situation [2, 3], these dynamometers, limited to size and structure factors, are out of place. New sensing devices should be researched and manufactured, whose indicators are special and quantity required is less, so a separate processing is necessary in the laboratory.

Crystal quartz, constituting wafer group [4], is the key of piezoelectric dynamometers. And crystal quartz plates are machined through rough slicing, direction determination, precise slicing, burnishing-and-grinding. Slicing quality plays a decisive role to indicators of the dynamometers, such as sensitivity and transverse interference of 3-axis. That is, slicing crystal quartz and acquiring high-quality surface are both important for the dynamometer. In this paper, several samples of crystal quartz have been sliced by traditional ping-pong wire saw machines, and the results are shown in Fig. 1, that out-of-straight slicing can be seen.



Fig. 1. Sliced crystal quartz sample out-of-straight.

In this paper, how to slice the crystal quartz well and straightly is researched. A review of the recent wire saw machining technology development is presented, first. A research system is built to measure 3-axis force. And slicing process is monitored by the system. The curves of three direction forces are obtained. Several conclusions are given by analyzing the curve. Then force analysis of diamond wire at changing direction is first shown and the conditions and reasons of out-of-straight slicing are discussed. Finally, some suggestions on slicing parameters and methods are put forward to overcome out-of-straight slicing.

2. Development of wire saw technologies

Slicing crystal quartz into thin wafers with minimum warp, uniform thickness, and low kerf loss has revitalized the interest in wire saw machining technology. However, band saw machining [5], which causes kerf loss, is unfit for high-cost crystal. The loose abrasive slurry saw machining with bare wire has been researched, in the 1990s. The loose abrasive saw causes environmental problem when the slurry is adjusted and is difficultly used to slice harder materials. With the development of electroplating technique, new diamond impregnated wires and wire saw machines with fixed diamond abrasive have been applied. Compared with traditional cutting methods, the fixed abrasive diamond wire has the advantage: low kerf loss, little pollution and slicing harder materials.

Considering the place twined diamond wire on and pattern of slicing, the wire saw machines are divided into continuous system [6] and ping-pong system [7]. The wire is welded together forming a ring in the continuous system, which only has one direction rotating and interference due to the welded place. In the ping-pong system, two sides of the wire are fixed respectively on one spool or two spools, which have positive and negative direction rotating and interference due to changing of direction, too. There are two forms, traditional and rocking motion [8] in ping-pong system of wire saw machines. In the rocking motion system, wire saw moves and samples are fixed while in the traditional system, it is opposite. In rocking motion system, complex structure of the system may lead to reduce rigidity, which is fit for slicing the big crystal. Therefore in this paper, traditional ping-pong system is used to slice the sample.

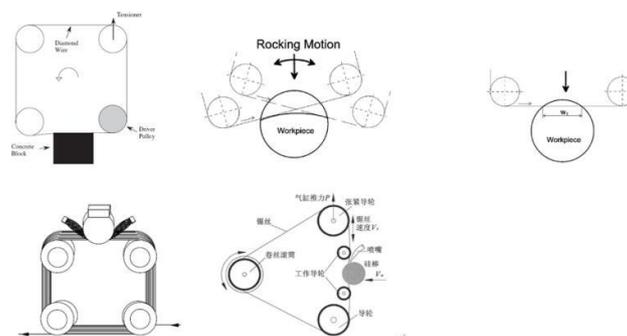


Fig. 2. Different kinds of the fixed abrasive diamond wire saw.

3. Experiment equipment

STX202, manufactured by MTI Auto-instrument Co., LTD, is selected as the experiment apparatus, as shown in Fig. 3. It has one spooler model, which is twined by a long wire, length 20 m.

Slicing crystal quartz and process monitoring techniques for diamond ping-pong wire saw machining are investigated by using a small precision diamond wire saw. The spooler is fixed on the screw rod. Rotating screw rod makes the spooler move along axial direction of the screw rod, and that makes sure sliced diamond wire rotate in the same plane. The stepping motor drives that wire spooler reverses direction periodically to produce the wire ping-pong

movement. The wire tension is provided by two tension springs and two auto-tension wheels during cutting. Two wire-guide pulleys are fixed with wire saw machines, keeping the wire movement straight to slice samples. The spooler's rotational speed is selectable between 0 and 260 n/min, 0 and 0.3 m/min. Crystal quartz is fixed on the sample plate. There are some adjustment mechanisms about the sample plate, for example, a micrometer is used to move the sample plate along X-axis. Another stepping motor provides vertical movement for the sample plate. The speed is selectable between 0.01 and 1 mm/min. The two stepping motors are controlled by stored program. Parameters are set by a matched function generator. Once the parameters are set, the wire saw machine is in motion at uniform velocity until the parameter has been adjusted. The diamond wire diameter is 0.3 mm, given by MTI Auto-instrument Co., LTD, also.

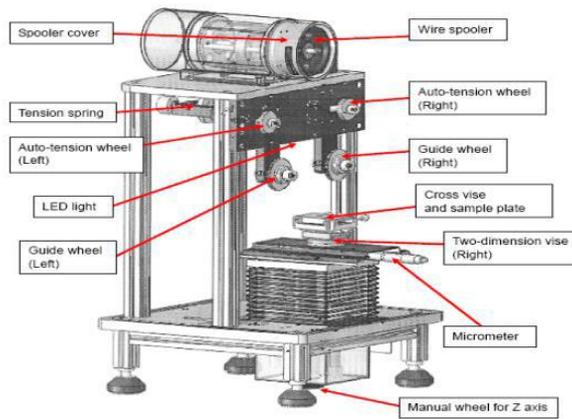


Fig. 3. The small precision diamond wire saw.

The sample, crystal quartz is provided by Jingyin Skyshine Opto-electronics Tech Co., LTD. The parameters are presented in Table. 1. The sample, 50*40*20 mm*mm*mm (X Y Z of quartz crystal orientation) has been machined first by manual circular saw. The sample is fixed on the sample plate with heated paraffin.

Table 1. Parameters of crystal quartz.

Z-axis thickness, mm	Q value	inclusion	Corrosion tunnel density, n/cm ³
20	>2.4*106	I	<10

4. The establishment of monitoring system

To research the slicing process further, the reason of slicing out-of-straight is discussed and a research and monitoring system is built.

Three-axis force of crystal quartz loaded by the diamond wire can be measured and monitored by the system in the Fig. 4.

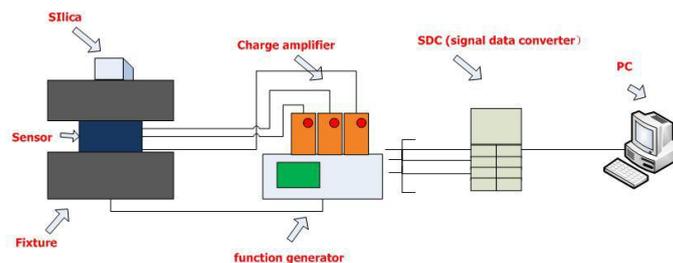


Fig. 4. Monitoring system diagram.

The monitoring system includes a fixture, a Kistler model 9255B three-axis force dynamometer, three Charge Amplifier Type 5018A machined by Kistler Co., Ld, A/D board machined by Dewetron Co., Ld, and a computer. A digital camera is used to monitor the wire bow angle.

5. Experimental procedures

Sensor is preloaded in the fixture by a hexagon socket head cap screw. The fixture is fixed in and moved with the sample plate. Three-axis of the sensor is consistent with samples, shown in Fig. 5.

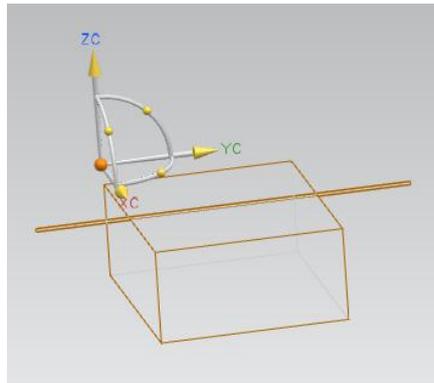


Fig. 5. 3-axis force of slicing process.

Similar to high speed grinding, high wire speeds can reduce the cutting force on diamond grit. Lower the wire wear and diamond pull-out, higher material removal rates achieved. The small precision diamond wire saw, a continuum with some flexibility and elasticity [10] provided tiny force for slicing. Due to the tension-spooler, there were initial tension forces before slicing.

When crystal quartz touched the moving wire, the slicing began. There were 3-axis forces on crystal quartz sample: Z-axis application forces provided by the wire bow; Y-axis application forces acted by the movement of the wire; X-axis application forces, whose reasons were complex, and lead to slice out-of-straight of crystal quartz. The feed speed of sample was constant value and selectable. The wire bow angle was defined as shown in Fig.6, including angle between the real wire and horizontal line. The wire bow angle kept changing during slicing process. In the experiment, feed distance was chosen longer 1-2 mm than thickness of crystal quartz sample for the wire bow angle. All the parameters were chosen, and the slicing proceeded automatically. When the slicing finishes, the sample plate returned automatically. Of course, the parameter can be modified on line, when the slicing process needed to be stopped.

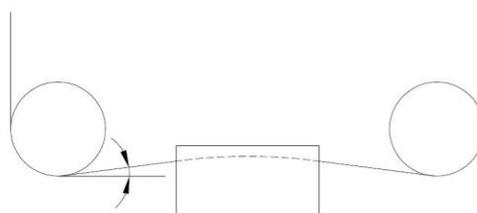


Fig. 6. The wire bow angle.

The curve of Z-axis force. Z-axis force was acted on the crystal quartz due to sample plate rising and wire bow angle beginning to appear. With sample plate rising, wire bow angle

became bigger. Return elasticity force of the wire was Z-axis force, just like, arrow load elasticity force of bowstring in bow and arrow. The Kistler piezoelectric force dynamometer shown in Fig. 4, was used to measure the force. Feed speed was 0.07 mm/min, rotational speed was 260 n/min, slicing depth is 10 mm. Three parts, A, B and C, was selected in the whole force curve for the long time of the whole slicing process (the same condition for Y-axis). And the wire bow angle was recorded in three parts, shown as Fig. 7.

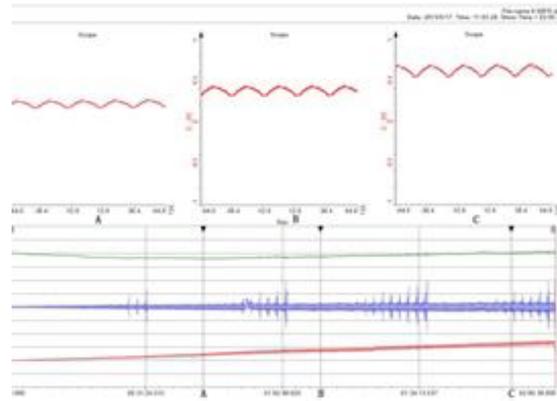


Fig. 7. The curve of Z-axis force.

According to Fig. 7, the value of Z-axis force was becoming larger, during slicing process. When crystal quartz touched the moving wire, the slicing began. As the feed speed was slow, wire saw kept approximate horizontal and the wire bow angle was small. In following parts, feed speed was faster than slicing speed. Bigger wire bow angle became, larger the Z-axis force became. When the sample reached the third tension-spooler, tension-force of the diamond wire became larger.

The curve of Y-axis force (horizontal cutting force). Horizontal cutting force was loaded on the crystal quartz due to the movement of diamond wire. As shown in Fig. 8, the direction of horizontal cutting force changed periodically. Period of changing direction was equal to the period of the spooler. The Period was estimated from the curve, depended on length of wire and rotational speed of spooler. Compared with part A, B and C, the horizontal cutting force was becoming larger, during the whole cutting process, with Z-axis force and tension-force increasing. Z-axis and Y-axis force ratio is shown in Fig. 9.

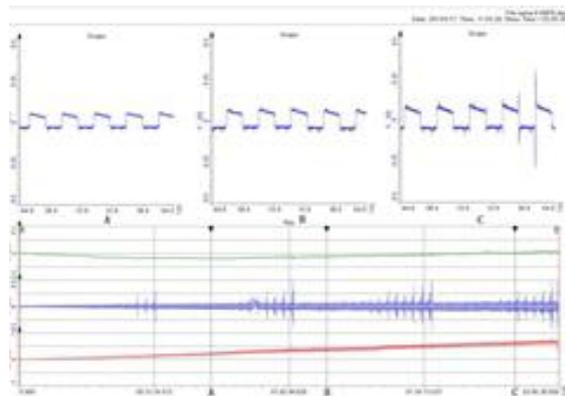


Fig. 8. The curve of Y-axis force.

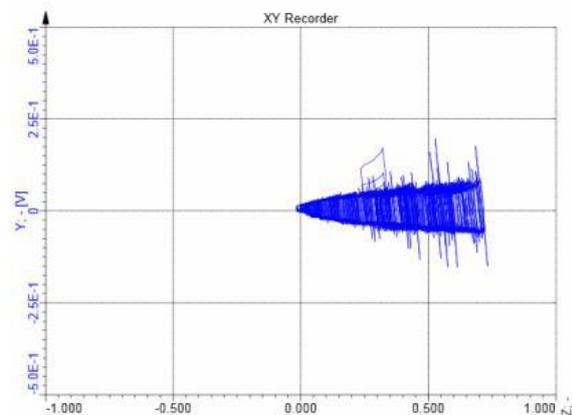


Fig. 9. Z-axis and Y-axis force ratio.

The fluctuation of horizontal cutting force at the changing direction was seen in the curve obviously. The ping-pong wire saw machine had only one spooler, where all of wires

were twined on. But not all of wires could be used to slice the material. The used length of wire was limited by two travel switches. The used and not used wire is seen in Fig. 10. The middle parts are used, where rust was found, as water was used for cutting fluid. Tension-force in the used and not used wire is different, used wire had larger tension-force due to crystal quartz feed as the third tension wheel.

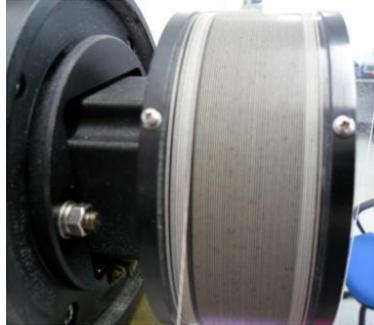


Fig. 10. Used and not used wire on the spooler.

X-axis force. The reason of X-axis force produced was explored, and problems of crystals quartz and wire saw were researched. Microcosmic shape of used wire was shot comparing with new one. It was found that the shape of fixed abrasive diamonds was inconsistent, as shown in Fig. 11. This kind of defect led to inconsistent X-axis force of wire. Also the defect of crystals quartz might lead to Z-axis force inconsistency, including crystal interior defects and radial surface shape. One example was shown in d and e of Fig. 1, irregular surface shape led to slicing out-of-straight. Additional transverse interference was caused due to shape mutation of radial surface on the crystal quartz. Slicing direction had been changed obviously at the mutation place.



Fig. 11. Micrograph of the broken diamond wire.

6. Discussion

The relationship between Z-axis force and tension-force. As shown in Fig. 7, Z-axis force, tension-force and wire bow angle have the same trend. That is, they are related in an equivalence. The tension-force has a maximum value, which depends on the ultimate strength of the diamond wire. The wire may be broken if the tension-force exceeds the maximum. On the other hand, slicing efficiency can be achieved at a larger tension-force. Therefore, choosing a suitable feed speed is important. While tension-force cannot be measured directly, Z-axis force or wire bow angle was used to estimate the tension-force.

The periodic fluctuation of Z-axis force. It is obvious that the Z-axis force has periodic fluctuations in Fig. 7. The phenomenon is discussed from deviation. B in Fig. 8, the direction of wire movement is left, as V1. Curve S2 is the main slicing surface, and less slicing happens in curve S1. The slicing forces are F12 and F11, shown in Fig. 12, whose Z-axis components are different. Opposite S2 was the main slicing surface when the direction of the wire was changed.

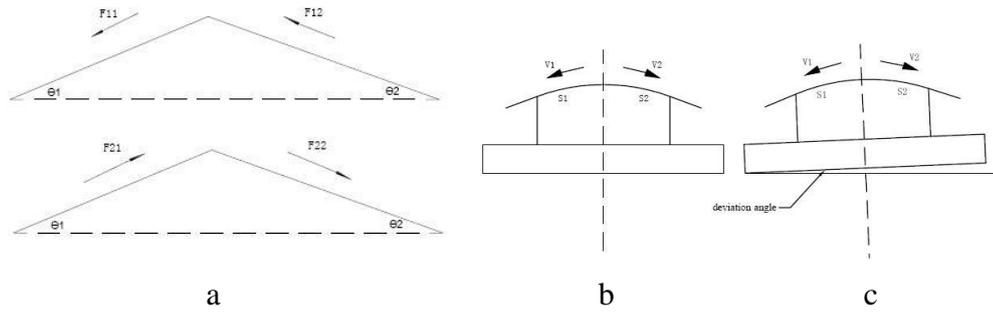


Fig. 12. The analysis of deviation of jig and fixture:
a) force analysis, b) ideal condition, c) deviation condition.

Due to symmetry, the resultant forces of two Z-axis component forces are invariant, no matter which direction.

$$\sum F_{Z1} = -F_{12} \sin \theta_2 + F_{11} \sin \theta_1, \quad (1)$$

$$\sum F_{Z2} = -F_{21} \sin \theta_1 + F_{22} \sin \theta_2, \quad (2)$$

$$\sum F_{Z1} - \sum F_{Z2} = \sin \theta_1 (F_{11} + F_{21}) - \sin \theta_2 (F_{12} + F_{22}). \quad (3)$$

When changing the direction, the parameters of slicing keep constant.

$$F_{11} + F_{21} = F_{12} + F_{22}, \quad (4)$$

$$\sum F_{Z1} - \sum F_{Z2} = (\sin \theta_1 - \sin \theta_2)(F_{11} + F_{21}), \quad (5)$$

In the ideal condition, when the sample is in the middle of the wire section between guide wheels,

$$\theta_1 = \theta_2, \quad (6)$$

$$\sum F_{Z1} = \sum F_{Z2}. \quad (7)$$

The force of Z-axis should be constant. However, in the reality condition, the sample is not in the middle.

$$\sum F_{Z1} \neq \sum F_{Z2}. \quad (8)$$

In the deviation condition, there is deviation of jig and fixture, as shown in c of Fig. 8, that symmetry of the Z-axis component loaded by two cutting forces is broken. The resultant forces of two Z-axis component forces are different, too.

Therefore, Z-axis curve has periodic fluctuation, which keeps rising tendency in the whole process. The fluctuation period is equal to period of changing direction. And the deviation is inevitable, as jig and fixture are machined and samples pasted.

The fluctuation of Y-axis force in changing direction. As shown in Fig. 13, a portion of diamond wire, AB is discussed, whose center angle is $d\theta$, from classical mechanics,

$$T_{out} = T_{in} e^{\mu\theta}, \quad (9)$$

where μ is friction coefficient between diamond wire and the spooler.

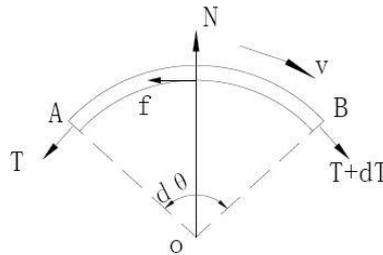


Fig. 13. Used and not used wire on the spooler.

Wire saw is loosened at the changing direction, and the tension-force is changed. There are always three to five unused circles of the wire, whose tension-force is different. The value of tension-force at fixed end of the wire was minimum. Also the value on unused wire keeps changing during slicing, so the wire spooler needs to be rotated from end to end manually, to reduce the fluctuation of horizontal cutting force in the changing direction.

The reason of slicing out-of-straight. In slicing process, X-axis force appears as transverse interference for slicing system. X-axis force loaded by diamond wire is the key of slicing out-of-straight. The maximum value of the measured X-axis force is 2N, when slicing out-of-straight. Oppositely, as slicing straight, the value of the force was near zero.

As shown in Fig.1, slicing out-of-straight can be seen at the beginning of slicing. It is supposed that tension-force is little at the beginning of slicing and crystal quartz slicing is easily influenced by X-axis force. A finite element analysis is done, demonstrating that tension-force is conducive to resist influence of X-axis force for slicing out-of-straight.

It indicates that when tension-force is increased at the beginning of slicing, crystal quartz would be machined well. Further, tension-force is kept constant in the whole slicing process, better result and efficiency of slicing would be acquired. Z-axis force instead of tension-force should be monitored and controlled in specific scope by force sensors by adjustment of Z-axis stepping motor movement.

7. Conclusion

The research system is built to monitor 3-axis forces. Cooling liquid should flow from guide wheels, not the sample, which can measure Z-axis force better. Z-axis force, the wire saw angle and tension are equivalence relation. Y-axis force has the same trend with Z-axis force, slicing efficiency is decided by Y-axis force. X-force force is the reason of slicing out-of-straight. Diamond deficiency, crystal quartz deficiency and irregular radial surface shape lead to X-axis force. Larger tension-force is conducive to resist influence of X-axis force. Therefore preload tension-force at the beginning of slicing is necessary. Keeping Z-axis force constant or in small scope by monitoring throughout slicing process is useful. Other factors e.g. slicing width, wire speed, crystal orientation should be researched in the further study.

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