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Experimental Study on Slicing of Sapphire with Fixed Abrasive Diamond Wire Saw

Mengjun Zhang, Yuli Sun, Dunwen Zuo, Chunxiang Xie, Chunming Zhang

***Abstract*—**Experimental study on slicing of sapphire with fixed abrasive diamond wire saw was conducted in this paper. The process parameters were optimized through orthogonal experiment of three factors and four levels. The effects of wire speed, feed speed and tension pressure on the surface roughness were analyzed. Surface roughness in cutting direction and feed direction were both detected. The results show that feed speed plays the most significant role on the surface roughness of sliced sapphire followed by wire speed and tension pressure. The optimized process parameters are as follows: wire speed 1.9 m/s, feed speed 0.187 mm/min and tension pressure 0.18 MPa. In the end, the results were verified by analysis of variance.

***Keywords*—**Fixed abrasive, diamond wire saw, slicing, sapphire, orthogonal experiment.

I. Introduction

SAPPHIRE is hard and brittle, having a hardness of 9 on MOHS scale, melting point of 2,053°C and a Young's modulus of about 414GPa [1]. The optical property, mechanical property and chemical stability of Sapphire are excellent. The surface smoothness of sapphire is good and the resistivity is high [2]. For these reasons, sapphire is widely applied in military equipments, space technology, semiconductor industry, and so on. Slurry wire saw was the first to be introduced for sapphire slicing process [3]. The slicing efficiency of this technique is high and the slicing quality is good. However, Slices by this method are easy to be deformed and the service life of wire is short. Besides, the recovery processing cost of slurry is expensive. Compared to slurry wire saw, the efficiency of fixed abrasive wire saw is higher. The cutting seam by fixed abrasive wire saw is narrow. The need for abrasives is less, which reduces the impact on the environment [4]. In addition, fixed abrasive wire saw can be used to cut large size materials. Because of these advantages, fixed abrasive wire saw has recently been used as an alternative to deal with sapphire and improve efficiency [5]–[7]. This study investigated the slicing of sapphire with fixed diamond wire saw.

Mengjun Zhang is with the College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China (e-mail: 15250953815@ 163.com).

Yuli Sun is with the Shanghai Institute of Space Control, Shanghai, 200233, China (phone: +86+02584891686; e-mail: sunyuli@nuaa.edu.cn).

Dunwen Zuo is with the College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China (phone: +86+13705158604; e-mail: imit505@nuaa.edu,cn).

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II. Experiment Equipments and Experiment Design

WXD-170 reciprocating wire cutting machine was used in this experiment. Fig. 1 shows its operating principle. The wire is rolled on the roller. It is driven by the roller and runs at the given speed. The tensioning wheel is pushed by air cylinder to supply needed wire tension. The work piece is driven by X mobile platform and machined in the area between two position wheels. The wire used in the experiment is produced by Asahi Diamond Industrial Co., Ltd. The diameter of the wire is 0.35 mm and the sizes of the diamond grains are 30 mm to 40 mm. The length of the wire on the roller is about 80 m.

The sapphire was sliced along C-plane. The roughness of the slices was measured with Perthometer roughness measuring instrument which is produced by MAHR. The work piece is irregularly columniform. For this reason, roughness in cutting direction and the roughness in feed direction were both measured. The roughness of point 1, point 2 and point 3 showed in Fig. 2 were measured and their average value was used as roughness in cutting direction. The average value of point 4, point 5 and point 6 was used as roughness in feed direction.

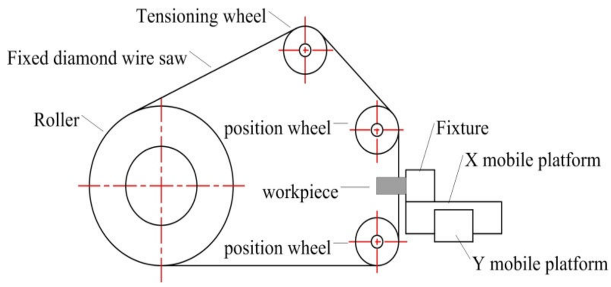

Fig. 1 Schematic diagram of WXD-170 reciprocating wire Cutting machine

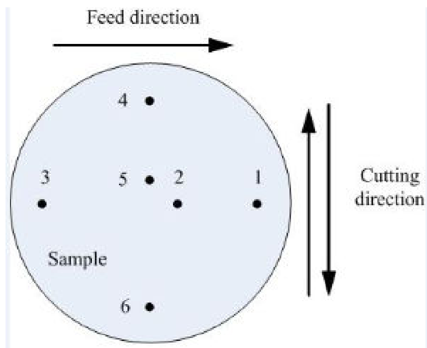

Fig. 2 Measurement method of roughness

The effects of wire speed, feed speed and tension pressure to the roughness were studied. The factors and levels of the orthogonal experiment are showed in Table I.

TABLE I
FACTOR LEVEL

Level	(A)Wire speed [m/s]	(B)Feed speed [mm/min]	(C)Tension pressure [MPa]
1	0.15	1.8	0.18
2	0.187	1.9	0.20
3	0.25	2.0	0.22
4	0.375	2.1	0.24

III. EXPERIMENTAL DATA AND ANALYSIS

Table II shows the measured values of roughness in cutting direction and Table III shows the values in feed direction. It can be found that the value of point 3 is far bigger than that of point 1 and point 2 in the 11th, 13th, 14th and 15th sets of the samples. This phenomenon was caused by the fast feed speed.

The work piece is columniform. For this reason, the material needed to be removed increased first and then decreased with the feeding of the work piece. When the feed speed was too fast, the wire could not slice the material effectively and then the wire between two position wheels became curve. An acting force contrary to the feed direction was generated in the contact zone of the wire and the work piece because of the tension of the wire. With the increase of the curve degree, the acting force increased. The material needed to be removed decreased with the proceeding of the slicing and then the acting force made the actual feed speed faster than the given feed speed. As a result, the cutting force increased which aggravated the squeezing and rubbing action. Then, the roughness worsened.

It could be found that the phenomenon did not occur in 12th and 16th sets of the samples. The reason was that the wire used in these samples was new. The attrition level of new wire was low and the slicing property of that was well, which avoided the wire curving. The several unusual roughness values would affect the real slicing quality. They were kicked off in the following calculation to guarantee the accuracy.

TABLE II
THE MEASURED VALUES OF ROUGHNESS IN CUTTING DIRECTION

No.	Roughness height in cutting direction [μm]			
	1	2	3	Average
1	0.324	0.285	0.377	0.329
2	0.368	0.337	0.385	0.363
3	0.355	0.415	0.353	0.374
4	0.364	0.532	0.461	0.452
5	0.358	0.346	0.361	0.355
6	0.400	0.272	0.355	0.342
7	0.377	0.307	0.326	0.337
8	0.388	0.367	0.348	0.368
9	0.400	0.449	0.418	0.422
10	0.386	0.331	0.323	0.347
11	0.404	0.325	0.302	0.344
12	0.405	0.348	0.323	0.359
13	0.419	0.405	0.421	0.415
14	0.344	0.307	0.348	0.333
15	0.361	0.441	0.287	0.363
16	0.379	0.314	0.373	0.355

TABLE III
THE MEASURED VALUES OF ROUGHNESS IN FEED DIRECTION

No.	Roughness height in feed direction [μm]			
	1	2	3	Average
1	0.661	0.621	0.714	0.665
2	0.608	0.691	0.678	0.659
3	0.562	0.622	0.530	0.571
4	0.522	0.579	0.581	0.561
5	0.699	0.506	0.633	0.613
6	0.618	0.454	0.444	0.505
7	0.591	0.525	0.576	0.564
8	0.579	0.535	0.549	0.554
9	0.923	0.788	0.741	0.817
10	0.596	0.594	0.656	0.615
11	0.500	0.522	1.284	0.511
12	1.180	0.860	1.189	1.076
13	1.953	2.109	2.670	2.031
14	0.886	0.790	1.400	0.838
15	1.187	0.846	1.762	1.017
16	0.891	0.913	0.920	0.908

IV. ANALYSIS OF THE ORTHOGONAL EXPERIMENT AND OPTIMIZATION OF PARAMETERS

The data of the orthogonal experiment is showed in Table IV. It could be found that the value of roughness in cutting direction is much smaller than that in feed direction. The reason is that the three selected points in cutting direction were sliced almost at the same time and then the slicing conditions, like the wearing of the wire, the vibration and so on, of these three points were very similar. So the roughness in feed direction is more suitable to reflect the actual roughness and the quality of slices than that in cutting direction. Besides, the average roughness value in feed direction is 2.2 times bigger than that in cutting direction. That means the roughness in feed direction is also more appropriate to reflect the differences of surface quality of different samples. For all these reasons, it could be conclude that analyzing the roughness in feed direction rather is much more meaningful. Then, the following analysis focused on the roughness in feed direction.

The range R of each factor could be found in Table IV. It is known to all that the bigger the range R is, the more influential the factor plays a role on the roughness. By analyzing the range in feed direction, feed speed has the most important impact on roughness and tension pressure plays the minimum part. In this experiment, small roughness is required and then the smallest one of k1, k2, k3 and k4 is needed. Then the optimized process parameters are as follows: wire speed 1.9 m/s, feed speed 0.187 mm/min and tension pressure 0.18 MPa. The process parameters of the sixth sample are same with the optimized process parameters. It can be found that the roughness values in cutting direction and in feed direction are both the optimal. This practical result agreed with the theoretical analysis. A set of repetitive test was made with the optimized process parameters. The roughness value in feed direction is 0.51 μm. The roughness is the most excellent expect for that of the sixth sample, which verified the analysis result.

The analysis of variance of the surface roughness in feed direction is showed in Table V. It is obvious that the mean square ratio of feed speed is the largest. The data shows that feed speed plays the most significant role on the surface roughness. Wire speed comes second. The mean square ratio of tension pressure is smallest and the effect of tension pressure to roughness is not prominent. The results agree with the results by using range method, which makes the results reliable.

TABLE IV
EXPERIMENTAL DATA

No.	Feed speed [mm/min]	Wire speed [m/s]	Tension pressure [MPa]	Roughness in cutting direction [μm]	Roughness in feed direction [μm]
1	0.15	1.8	0.18	0.329	0.665
2	0.15	1.9	0.20	0.363	0.659
3	0.15	2.0	0.22	0.374	0.571
4	0.15	2.1	0.24	0.452	0.561
5	0.187	1.8	0.20	0.355	0.613
6	0.187	1.9	0.18	0.342	0.505
7	0.187	2.0	0.24	0.337	0.564
8	0.187	2.1	0.22	0.368	0.554
9	0.25	1.8	0.22	0.422	0.817
10	0.25	1.9	0.24	0.347	0.615
11	0.25	2.0	0.18	0.344	0.511
12	0.25	2.1	0.20	0.359	1.076
13	0.375	1.8	0.24	0.415	2.031
14	0.375	1.9	0.22	0.333	0.838
15	0.375	2.0	0.20	0.363	1.017
16	0.375	2.1	0.18	0.355	0.908
Roughness in feed direction					
k1	0.612	1.031	0.647		
k2	0.560	0.654	0.841		
k3	0.755	0.666	0.695		
k4	1.199	0.775	0.942		
Range R	0.639	0.377	0.295		

TABLE V
ANALYSIS OF THE SURFACE ROUGHNESS IN FEED DIRECTION

Source	Sun of Squares (SS)	Freedom (F)	Mean square (Ms)	Mean square ratio (F)
A	1.010	3	0.337	6.358
B	0.366	3	0.122	2.302
C	0.212	3	0.071	1.340
Error	0.160	3	0.053	
Total	1.748	12		

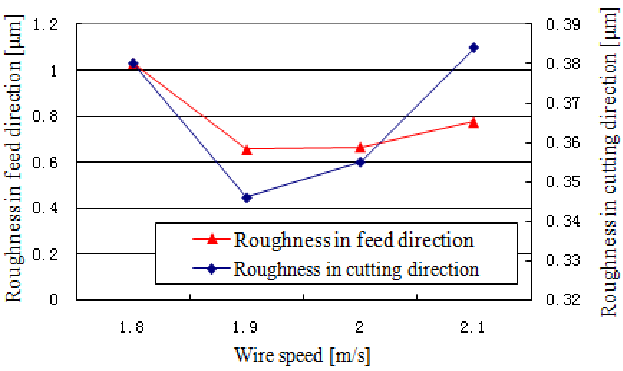

Fig. 3 Influence of wire speed on surface roughness

V. THE EFFECTS OF PROCESS PARAMETERS TO THE ROUGHNESS

Fig. 3 shows the surface roughness's relationship with wire speed. The change trends of roughness in feed direction and in cutting direction with wire speed are similar. The roughness decreased when the wire speed from 1.8 m/s to 1.9 m/s and then increased with the growing of wire speed.

Assuming that the material occur by the plastic deformation, the force on an individual diamond particle F_{zg} can be expressed as [8]

$$F_z = F_{zg} = \pi\sigma_y Rh \tag{1}$$

where F_z is vertical force on a particle, σ_y is yield stress of the work piece, R is radius of a spherical particle, h is the depth of penetration by a particle.

During machining, the vertical force on a particle F_z can be written as [9]

$$V_z = \frac{d}{dt}\left(\frac{Vol}{A_p}\right) = \frac{d}{dt}\left(\frac{\frac{L_o}{L_g}\times D\times h\times s}{L_o\times D}\right) = \frac{ds}{dt}\left(\frac{h}{L_g}\right) = V_x\left(\frac{h}{L_g}\right) \tag{2}$$

where V_z is feed speed, Vol is volume of the material needed to be removed, A_p is cross-section area of the trace of a particle, L_o is slicing length of the sample, L_g is distance between the neighboring particles, D is diameter of the wire, s is distance traveled by a sharp particle, V_x is velocity of the wire.

From (1) and (2), we obtain:

$$F_{zg} = \pi\sigma_y RL_g \times \frac{V_z}{V_x} \tag{3}$$

$$h = L_g \times \frac{V_z}{V_x} \tag{4}$$

It can be found that the force on an individual diamond particle is proportional to the depth of penetration by the particle from (1). The depth of penetration increases with the growing of feed speed and decreases with the growing of wire speed from (4). With the increase of wire speed, the depth of penetration by a particle should decrease in theory. Then, the roughness of the sections would be small.

However, the length of wire on reciprocating wire cutting machine is limited. Then, the wire needs to reverse cutting direction during machining. During this process, the speed of wire decreases to zero gradually and then increase to the setting level while the feed speed do not change, which will lead the generation of scratches [10]. As a result, fast wire speed leads to frequent reversing of the wire and more scratches generate on the surface of the samples. These scratches exacerbate the roughness. Besides, the cutting machine vibrates violently when the wire speed is too fast, which deepens the depth of scratches and makes the roughness bad.

In this experiment, it could be conjectured that when the wire speed was under 1.9 m/s, the decrease of the depth of penetration by a particle with the increase of wire speed played the most significant role on the surface roughness of samples. When the wire speed continued to increase, the influence of the vibration and scratches due to frequent reversing were more observable than that of the decrease of the depth.

Fig. 4 shows the surface roughness's relationship with feed speed. The change trend of roughness in feed direction with feed speed is similar with that in cutting direction. Overall, the roughness decreases with the increasing of the feed speed when the feed speed is under 0.187 mm/min. Then the roughness increases with the growing of wire speed. The acting force is proportional to feed speed in theory from (3). It increases with the growing of the feed speed and then the squeezing and rubbing action are aggravated. As a result, the roughness worsens. Moreover, the increasing of feed speed leads to the growing of the residual height, which increases the roughness. When the feed speed is too fast, the wire becomes curve which also has a negative effect on the roughness. The change trend from 0.15 mm/min to 0.187 mm/min of feed speed may be caused by the measuring error of roughness values.

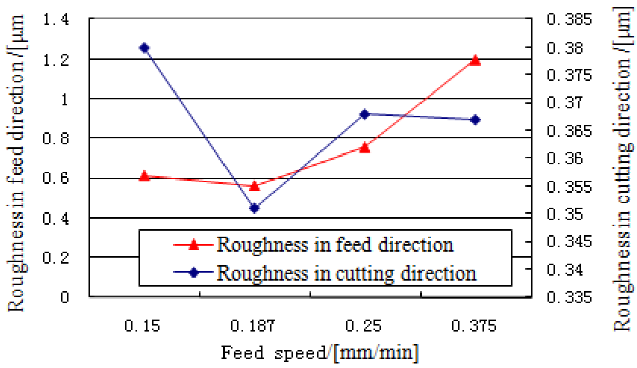

Fig. 4 Influence of feed speed on surface roughness

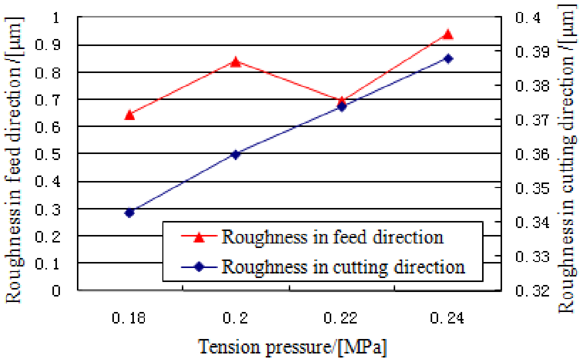

Fig. 5 Influence of tension pressure on surface roughness

Fig. 5 shows the surface roughness's relationship with tension pressure. The roughness in cutting direction increases with the growing of tension pressure. On the whole, it can be observed that the roughness in feed direction floatingly increases with the growing of tension pressure. This phenomenon was caused by the cross influence of vibration and tension pressure. On the one side, for the long-term using of the position wheels, the groove of the wheel generates some small traces. When the cylinder pressure is high, the tensile force is large and the wire contacts closely with the groove. As a result, it is easy for the wire to be squeezed into these traces. Then, the vibration of the wire is aggravated, which makes the roughness bad. One the other hand, when the cylinder pressure is low, the wire is easy to curve during slicing. The curve of the wire leads to the skewing of the slicing track, which increases the roughness. With the increase of the tension pressure, the curve of the wire can be reduced efficiently. Then, the roughness can be decreased. Taking no account of the effect of traces, with the increase of tension pressure, the vibration is reduced and the wire moves stable. The roughness can be reduced. Taking all these factors into consideration, the floating increase of the roughness in feed direction with the growing of tension pressure can be explained.

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