AN EXPERIMENTAL STUDY OF THE EFFECT OF ULTRASONIC VIBRATION ASSISTED WIRE SAWING ON SURFACE ROUGHNESS OF SIC SINGLE CRYSTAL

Xiaoye WANG[1]

ABSTRACT: Because of excellent electrical properties and excellent physical and chemical properties, SiC single crystal is widely used in integrated circuits and optical electronic devices. Its production process includes cutting, grinding, polishing, detection, etc. Among these links, cutting is the most critical and cost-efficient one. Due to extreme hardness and high brittleness, SiC single crystal is very likely to have surface roughness and cracks during cutting. In this paper, the technical background of SiC single crystal cutting is introduced, and the principle of ultrasonic vibration assisted cutting technology is described. Changes in SiC single crystal surface roughness at varying feeding speed and wire running speed during cutting were studied, through a contrast experiment of ultrasonic vibration assisted wire sawing and traditional wire sawing. The experiment result suggests that, under the same machining conditions, the surface roughness level of SiC single crystal after ultrasonic vibration assisted wire sawing is 40.6% lower than that after traditional wire sawing.

KEY WORDS: ultrasonic vibration, wire sawing, SiC single crystal, surface roughness, experimental study.

1 INTRODUCTION

SiC single crystal, namely silicon carbide, is the 3rd generation of one of major semi-conductor materials. It is widely applied in high temperature and high frequency, photo-electronic integrated circuit and micro-electronics for its electrochemical advantages of extreme hardness, strong corrosion resistance, resistance to high temperature and radiation, good thermal conductivity, and low dielectric constant (Zhao et al., 2011; Huminic et al., 2016). At present, with the breakthrough in production technology, the sales volume of SiC single crystal is growing at an annual rate of 19.7% on the semiconductor market. SiC has a broad application prospect. Mohs hardness of SiC is 9.2, only poorer to diamond, and its brittleness is great. For such a hard-brittle material, cutting is generally the bottleneck of its production. SiC crystal cutting costs 50% as much as its production costs. Besides, crystal surface is very likely to be rough or cracking during cutting (Han, R. et al., 2003). Therefore, it is an urgent task to research into the SiC cutting technology so as to achieve high-efficiency, high-precision, high-quality and low-cost processing of SiC single crystal (Yamamura et al., 2011).

Now, major SiC cutting technologies include free-grain wire sawing, fixed-grain wire sawing, diamond saw blade cutting and electric spark machining (EDM) (Ishikawa et al., 2014; Bonţiu and Lobonţiu, 2015).

[1]Baoji University of Arts and Science, Baoji 721016, China

E-mail: 157149890@qq.com

Internationally, many scholars research on SiC cutting. Some of them hold that the work piece feeding speed influences the surface roughness of single crystal most and that additional rotation can reduce the surface roughness. Also, some cut Zirconium dioxide and ceramics by using ultrasonic vertical vibration, achieving a good result of surface roughness (Tsai, 2011; Coman et al., 2016; Straka and Hašová, 2016).

Vibration assisted cutting is, in principle, to improve the motion state and cutting property of grains during cutting through vibration and secondly to solve problems such as chip removal, thermal dissipation and cutting line breaking existing in cutting. Thus, it can significantly reduce the thickness of damaged layer and the surface roughness of cut piece (Matsumura et al., 2012). For this reason, ultrasonic vibration is introduced in this paper. Its working principle and equipment components are introduced, and the principle of ultrasonic vibration assisted cutting is described. In the experiment stage, changes in SiC single crystal surface roughness in the case of varying feeding speed, wire running speed, and grain diameter were analyzed through ultrasonic vibration assisted wire sawing and through common wire sawing respectively, and the experiment results were analyzed too. Then, a data based conclusion was reached. In theory, this paper is of significance to the guidance on SiC single crystal cutting, reduction of cutting cost, and improvement of cutting quality.

2 RESEARCH STATUS AND THEORETICAL BASIS

2.1 Status of SiC wire sawing technology

2.1.1 Cutting methods

At present, there are two traditional methods applicable to SiC single crystal cutting: free-grain wire sawing and fixed-grain wire sawing.

Free-grain wire sawing: Its principle is to reduce the surface roughness of cut piece through "rolling-forcing" of free grains and cut piece. Cutting fluid is necessary for grinding. Despite high grinding quality and low wastage rate, this method has such disadvantages as low cutting speed and great difficulty in thickness control (Huang et al., 2012). Thus, free-grain wire sawing is not suitable for the high-speed precision cutting of SiC single crystal slices.

Fixed-grain wire sawing: For this method, the cutting tool is high-strength stainless steel wire consolidated by surface diamond, which becomes the best choice to cut SiC single crystal for good abrasion resistance and good heat resistance (Cvetković et al., 2011). Advantages of fixed diamond cutting include fewer micro-cracks, narrow cutting seams, less environment pollution for no need for cutting fluid. However, for SiC crystal with high Mohs hardness, the cutting efficiency is low, and the cutting line wears seriously.

2.1.2 Cutting modes

Wire sawing of such hard-brittle material as SiC single crystal has three modes: straight-pushing cutting; swing cutting; work-piece rotary cutting. Straight-pushing cutting: The length of contact between saw wire and crystal bar keeps varying during cutting. Swing cutting: During cutting, the cut piece keeps still, and the diamond fretsaw mounted below a frame does swing cutting at a certain angular speed. Work-piece rotary cutting: At the same time of straight-pushing cutting, SiC crystal bar rotates along the axis at a varying angular speed (Bhagavat & Kao, 2006).

2.2 Wire sawing devices

At present, internationally famous manufacturers researching into multi-wire sawing devices include HCT, Neyer Burger (Switzerland) and NTC (Japan). A typical model of wire cutting device is shown in Figure 1.

In this figure, NWS-610SD is the typical product under a Japanese band of TAKATORI; E4000E-12-C is the typical product under a Swiss band of HCT; DS-264 is under Meyer Burger. All of them are special types of precision CNC machines for multi-wire cutting. Their control system is complicated, processing precision is high, and parts are so many (Wang et al., 2017).

(a) NWS-610SD (b) E400E-12-C

(c) DS-264

Figure 1. The representative sawing machines

In our country, the semi-conductor cutting technology develops is late. We need always introduce cutting devices from other countries and do not have many independently developed models. However, with the development of semiconductor industry and the high attention from national manufacturing industry, China has made a great progress in the research and development of precision CNC cutting machines in recent years. DXQ-601 cutting machine independently developed by CETC (China Electronics Technology Group Corporation) has a low wastage rate and a high passing rate of finished products up to 99.7%. The 2nd generation of XQ300A CNC multi-wire sawing machine launched by Hunan Yujing Machine Industrial Co., Ltd. is characterized by high wire running speed, high cutting speed, high stability and synchronicity.

2.3 Theoretical basis and principle of ultrasonic assisted wire sawing

2.3.1 Theoretical basis

In ultrasonic vibration assisted wire sawing, the work piece is stimulated by ultrasound to produce resonance so that it can be wire sawn at an ultrasonic frequency while the fretsaw moves back and forth (Yan et al., 2012).

Ultrasonic cavitation is a phenomenon occurring when high-strength ultrasound radiates in liquid. The nucleus of micro-bubble vibrates under the influence of ultrasound. At a certain air pressure, the bubble will inflate rapidly before sudden closure. When the bubble is closed, shock waves come into being. This series of dynamic processes “inflation, closure, vibration” are called ultrasonic cavitation (Xiang et al., 2014). In the presence of ultrasonic vibration, grains impact the machined surface continuously, with a terrific impact load applied to the work piece cut area, causing plenty of micro horizontal cracks in the cut area. It facilitates cutting in next stage. Under the influence of ultrasonic cavitation, powdered chips and grains dropping down rub the machined surface together at a high frequency, which is actually equivalent to grinding. This can significantly improve the surface machining quality of slices (Siddiq & El, 2012; Lei et al., 2015).

2.3.2 Cutting principle

In this paper, ZGD100A reciprocating diamond cutter is refitted for additional ultrasonic vibration horizontally. The ultrasonic vibration system consists of ultrasonic generator, energy converter, amplitude transformer and corresponding fixtures. In this system, the ultrasonic power supply converts 50 Hz alternating current into ultrasonic frequency electrical oscillation signals; the energy converter converts oscillation signals into ultrasonic frequency mechanical vibration signals; the amplitude transformer amplifies vibration; vibration signals are transmitted to the tool. Finally, the tool machines the work piece with certain energy.

Figure 2 shows the system diagram.

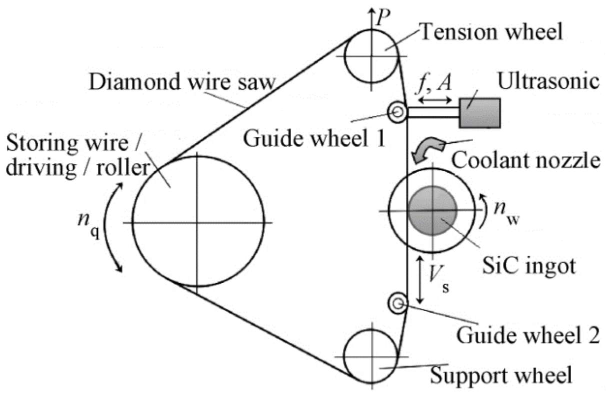

Figure 2. The schematic of ultrasonic-assisted wire saw

Working principle of ultrasonic assisted cutting system: the single crystal SiC bar is fed perpendicularly to fretsaw at v_x while rotating at n_w; the diamond fretsaw is driven by roller at v_s in both directions. As regulated by the control system, roller starts rotate anticlockwise once the maximum wire length is reached in clockwise direction, thereby achieving reciprocating motion of wire sawing. During cutting, the fretsaw supported by a pair of tensioning guide pulleys keeps tensile, without bending. The direction of ultrasonic vibration is perpendicular to the fretsaw moving direction and the axial direction of single crystal SiC bar.

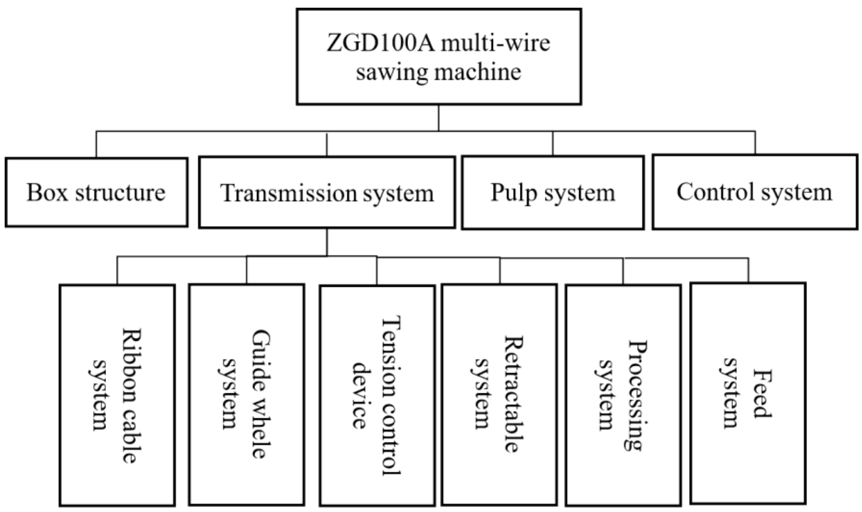

Figure 3. Overall scheme design of multi–wire sawing machine

Figure 3 shows the overall plan of ZGD100A multi-wire cutting machine. This system consists of box, transmission system, slurry feed system, and control system.

System requirements: Machine cutting should be steady without obvious vibration, and both wire running speed and feeding speed should be adjustable. Production requirements: It can satisfy the need of batch production, high surface quality, and high shape accuracy.

3 EXPERIMENTAL DESIGN

3.1 Experimental device

Experimental device: ZGD100A multi-wire cutting machine. Its performance parameters are given in Table 1.

Table 1. The performance parameters of the device

Maximum wire saw speed(m/s)	Line tension control accuracy	Minimum feed speed (mm/min)	The maximum amplitude of the workpiece	Coolant jet flow (L/min)
6	±2	0.05	12	5

Materials: SiC crystal bar (diameter: 50mm; crystal slice thickness: 0.8mm) produced with PVT method to be cut along the (0001) crystal face; grain carrier, as cutting line, to bear a tensile force; copper zinc plated stainless steel wire with a diameter of 130μm; 240#, 400# and 600# green silicon carbide grains, with average diameter of 44.5μm, 17.3μm, 9.3μm respectively; PEG (polyethylene glycol) with good lubricity and cohesiveness, as cutting fluid.

3.2 Experimental purpose

Experimental purpose: to analyze the effect of ultrasonic assistance on crystal surface roughness (Bhushan et al., 2010) by comparing ultrasonic assisted wire sawing of mono-crystal SiC with its common wire sawing; to analyze the effect of varying feeding speed and wire running speed on the surface roughness of SiC single crystal. This study is, on one hand, to demonstrate the effect of ultrasonic vibration assistance on improving the cutting surface quality of SiC single crystal and, on the other hand, to provide the theoretical guidance on the feeding speed and wire running speed of wire sawing.

3.3 Acquisition of experimental data

Surface roughness, microstructure of damaged layer, and residual stress are several reference indicators of SiC single crystal surface quality (Rogdakis et al., 2009). This study focuses on the measurement of surface roughness. Measurement method: Take 5 rows of parallel lines (A~E) with the same spacing in the cutting line running direction; select 10 points from each row of line as test points; measure the roughness at these points by using Mitutoyo roughness tester. At the same time, in order to ensure the accuracy of test results, take 3 cutting slices of SiC crystal for roughness measurement and do a statistic analysis of average values as experiment results, in the case of ultrasonic vibration assisted cutting and common cutting respectively.

4 EXPERIMENT RESULTS

4.1 Relationship of surface roughness with wire running speed, ultrasonic vibration assistance existing or not

Given that the grain diameter is 400# and that the feeding speed is 0.3 mm/min, measure the surface roughness value of SiC single crystal slices, in cases where ultrasonic vibration assistance exists and where it does not exist respectively.

Compare the crystal surface roughness more intuitively between ultrasonic vibration assisted wire sawing and common wire sawing, as shown in Figure 4.

Table 2. The slice surface roughness value (1)

Item	Feed speed	Partical size	Wire saw speed	Frequency(Hz)	Roughness Ra(μm) Mean Value			
1	0.3	400#	3	0	1.53	1.46	1.68	1.56
2	0.3	400#	4	0	1.31	1.26	1.24	1.26
3	0.3	400#	5	0	1.12	1.19	1.05	1.12
4	0.3	400#	3	20K	0.97	0.91	0.82	0.90
5	0.3	400#	4	20K	0.92	0.85	0.72	0.83
6	0.3	400#	5	20K	0.81	0.83	0.77	0.82

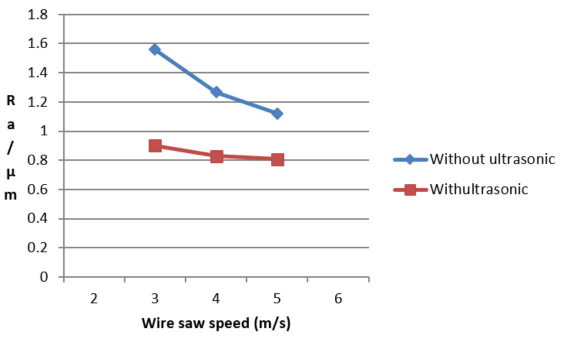

Figure 4. The relation of wire saw speed and roughness with or without ultrasonic

From Table 2, we can know that the surface roughness of slice decreases with the increase in wire running speed in both cases. The reason should be that, as the wire running speed increases, dynamic grains participating in cutting become more. However, since the number of grains that can participate in cutting is limited, the surface roughness would finally tend to be stable, even if the wire running speed still increases (Mishra et al., 2014).

From Figure 4, we can see that, compared with common wire sawing, the surface roughness of SiC crystal is lower and its surface quality is much higher in the case of ultrasonic vibration assisted wire sawing. For example, when the wire running speed is 4m/s, the average surface roughness is 0.83 in the case of ultrasonic vibration assisted wire sawing but is 1.26 in the case of common wire sawing. At the same wire running speed, the surface roughness value in the case of ultrasonic vibration is 34.1% lower than that in the other case.

4.2 Relationship of surface roughness with feeding speed, ultrasonic vibration assistance existing or not

Given that the grain diameter is 400# and that the wire running speed is 4m/s, measure the surface roughness value of SiC single crystal slices, in cases where ultrasonic vibration assistance exists and where it does not exist respectively.

Table 3. The slice surface roughness value (2)

Item	Feed speed	Partical size	Wire saw speed	Frequency(Hz)	Roughness Ra (μm) Mean Value			
1	0.1	400#	4	0	1.07	0.92	0.94	0.98
2	0.3	400#	4	0	1.31	1.26	1.24	1.26
3	0.5	400#	4	0	1.93	2.02	1.97	1.97
4	0.1	400#	4	20K	0.68	0.62	0.57	0.61
5	0.3	400#	4	20K	0.93	0.85	0.72	0.83
6	0.5	400#	4	20K	1.21	1.13	1.17	1.18

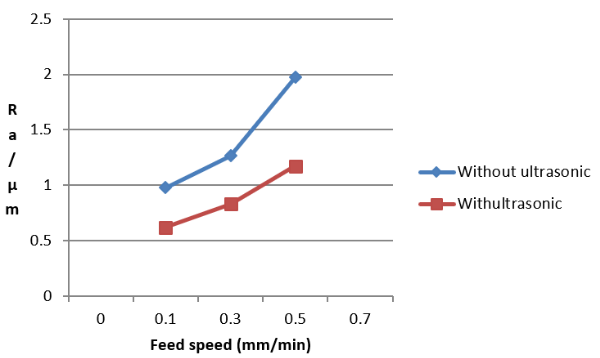

Figure 5. The relation of feed speed and roughness with or without ultrasonic

From Table 3, we can know that the surface roughness of slice increases with the increase in feeding speed in both cases. Possible reason: As the feeding speed increases, the rate of cutting line removing crystal work pieces gets lower. Grains contacting crystal decrease but a single grain cuts deeper, which makes slice surface cutting deeper. What's more, as the feeding speed increases, abrasion between fretsaw and work piece becomes more serious, increasing surface scratches and further causing a rise in roughness. Even in the case of common wire sawing, the cutting line bends seriously when the feeding speed increases to 0.7 mm/min. Therefore, the feeding speed should be not too high but proper. Of course, a too low feeding speed will also influence the work piece machining efficiency, causing time waste.

From Figure 5, we can see that ultrasonic vibration can significantly reduce the surface roughness of SiC crystal, leaving out feeding speed. For instance, when the feeding speed is 0.5 mm/min, the average surface roughness is 1.17 in the case of ultrasonic vibration assisted wire sawing but is 1.97 in the case of common wire sawing. At the same feeding speed, the surface roughness value in the case of ultrasonic vibration is 40.6% lower than that in the other case.

4.3 Result analysis

When ultrasound motivates the work piece to produce resonance, the work piece vibrates at an ultrasonic frequency at the same time of fretsaw reciprocating. In the presence of ultrasonic vibration, grains impact the machined surface continuously, with a terrific impact load applied to the work piece cut area, causing plenty of micro horizontal cracks in the cut area. This facilitates cutting in next stage. Under the influence of ultrasonic cavitation, powdered chips and grains dropping down rub the machined surface together at a high frequency, which is actually equivalent to grinding. This can significantly improve the surface machining quality of slices.

5 CONCLUSIONS

This paper first introduces the status of international research on SiC single crystal cutting and main cutting technologies, modes and second introduces the ultrasonic vibration assisted cutting technology. Then, a contrast experiment of ultrasonic vibration assisted cutting and regular cutting goes. Through this experiment, we come to the following conclusions:

(1) Ultrasonic vibration assisted cutting can significantly reduce the crystal surface roughness and improve the SiC crystal machining quality. This technology should be promoted in SiC crystal machining.

(2) During SiC crystal machining, the work piece feeding speed and wire running speed should be proper, for assurance of machining quality and efficiency.

(3) When the wire running speed is the same, the surface roughness in the case of ultrasonic assisted wire sawing is 34.1% lower than that in the case of regular cutting; when the feeding speed is the same, this difference is 40.6%.

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