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Shape-cutting of quartz glass by spark discharge-assisted diamond wire sawing

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ABSTRACT

Shape-cutting of quartz glass is difficult due to its high hardness, brittleness, and electrically insulting properties. This paper explores shape-cutting of quartz glass by spark discharge-assisted diamond wire sawing. The spark discharges were generated around diamond wire based on wire electrochemical discharge machining (WECDM). In the NaOH electrolyte, chemical etching of quartz glass took place with the occurrence of spark discharges. The chemical etching products were immediately removed by the quickly moving diamond wire. The diamond wire could keep straight with appropriate process parameters, which is essential to ensure machining accuracy. Experiments were conducted to analyze the effects of applied voltage, wire speed, and workpiece feed rate on machining performance. The diamond wire bending was measured to study the cause of poor machining accuracy. In addition, the overcut by spark discharges was presented close to the workpiece surface. To solve this problem, two thin soda-lime glass plates were put on the top and bottom surfaces of the quartz glass. As a result, the overcut only existed on the soda-lime glass, and good machining accuracy was achieved on quartz glass.

1. Introduction

Quartz glass has been widely used in micro electromechanical systems (MEMS) and micro-fluidic devices, owning to the characteristics of transparency, electrical insulation, high hardness, high corrosion resistance, and high temperature resistance [1]. However, quartz glass is difficult to cut due to its high hardness and brittleness. Wire electrical discharge machining (WEDM) does not work because quartz glass is electrically insulating. Laser beam machining [2] is a solution of cutting insulating hard and brittle materials, but the precision laser cutting machine is expensive. Abrasive water jet [3–5] was also used to cut insulating materials, but the slit width was large, and the angle of the cutting surface was obvious and unavoidable. By decomposing the kerosene, carbon layer was generated and deposited on the workpiece, therefore electrical discharge machining was tried in cutting insulating materials, but the process was unstable and uncontrollable [6].

To improve the quality of machined quartz glass, wire electrochemical discharge machining (WECDM) was proposed, which utilized the chemical etching effects of the workpiece. In WECDM, the tool wire and the auxiliary electrode are connected to the negative and the positive poles of the DC power, respectively. The electrolyte is supplied to the cutting zone to connect the tool wire and the auxiliary electrode, and thus a circuit is generated. When the voltage is applied, the hydrogen gas is generated on the tool wire surface. With the increasing voltage, the amount of hydrogen gas increases, which finally forms hydrogen gas film around the tool wire. The hydrogen gas film isolates the tool wire from the electrolyte, and so an open circuit is generated. When the voltage exceeds the critical value, electric breakdown happens to the hydrogen gas film and spark discharges are generated. The work material close to the spark discharges is removed under the high temperature circumstance. Borosilicate glass and e-glass fiber epoxy composite were machined by WECDM with horizontal wire immersed in electrolyte [7,8]. The electrolyte level should be strictly controlled because the buoyancy and surface tension effects have a significant influence on the generation of hydrogen gas film. In addition, partial discharge energy was wasted because a segment of wire produced spark discharges but didn't contact with the workpiece. Through flushing the electrolyte towards the wire moving direction instead of submerging the wire in electrolyte, the discharge process was improved [9]. Kuo et al. [10] applied titrated electrolyte flow to WECDM and the stable discharge was obtained. The precision control of the electrolyte flow rate is important to the machining efficiency and quality. Rattan et al. [11] used magnetic field to improve the electrolyte circulation in machining zone, and the experimental results showed that the material removal rate (MRR) was increased. Although the WECDM process was improved, the physical contact between the wire and the workpiece was

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not avoided, which caused the lack of electrolyte in the machining zone. The insufficient supplement of electrolyte led to low MRR and rough machined surface. Yang et al. [12] added SiC abrasive to electrolyte to maintain an appropriate gap between the wire and the workpiece. However, the dissociative abrasive disrupted the bubble accumulation, which was negative to the hydrogen gas film generation. Additionally, the above introduced WECDM research was conducted on horizontal wire setup. It makes the design of machine tool difficult, especially in machining parts which require multi-axis control. Therefore, most of the WECDM research is about cutting straight slit, and the shape-cutting is rarely involved.

Free abrasive wire cutting method [13–16] can be used to cut quartz glass, but the cost of recycling and retreating the slurry is high. As an improved process, diamond grits were fixed on steel wire to generate the diamond wire [17–20]. In order to improve the machining efficiency, WECDM was integrated with diamond wire sawing [21,22]. The NaCl solution was used as the electrolyte, which was dropped to the cutting zone with a flow rate of 32 ml/min. Spark discharges were generated on the vertical diamond wire and the MRR was increased. The surface topography of machined samples showed that the spark discharges facilitated the spalling of work material instead of melting it. The diamond grits also ensured a gap between the wire and the workpiece to improve the electrolyte circulation. Since the diamond grits were fixed on the wire, the disruption of the bubble accumulation caused by adding particles to the electrolyte was eliminated. However, the spark discharge process was still unstable because of the vulnerable hydrogen gas film. To solve this problem, oil film was covered on the diamond wire [23]. Experimental results showed that stable spark discharges were achieved in cutting of a 30.0 mm thick quartz glass on a vertical wire setup. The voltage should not exceed 58 V, or else the diamond wire would quickly break. But, shape-cutting of quartz glass is still not achieved. Basak et al. [24] reported that the removed glass was negligible by spark discharges in NaCl electrolyte when the voltage was below 60 V, which meant that the glass can hardly be etched or melted. The quartz glass can also hardly be softened since the electrochemical discharge temperature was only around 600 °C [25]. The diamond wire must exert a relative large force on the workpiece to remove the work material. Such force was exerted by a counterweight that pulled the workpiece to feed on a slide guide [21–23]. Therefore, the diamond wire was bent during machining, which cannot ensure the machining accuracy, especially when the cutting path contains arc.

This paper applied NaOH solution as the electrolyte in spark discharge-assisted diamond wire sawing. The workbench took the workpiece to move with a constant feed rate. Under the spark discharge condition, chemical etching of quartz glass happened. The quickly moving diamond grits immediately removed the chemical etching products on the premise of keeping a straight diamond wire. The new exposed quartz glass continued to be etched to ensure continuous material removal. Experiments on cutting of a circular profile on quartz glass were conducted on a vertical wire setup, and the effects of applied voltage, wire speed, and workpiece feed rate on machining performance were analyzed. The diamond wire bending was measured to study the cause of poor machining accuracy. This research provides an experimental basis for the shape-cutting of quartz glass by spark discharge-assisted diamond wire sawing.

2. Experiments

2.1. Experimental setup

Fig. 1 shows the experimental setup of shape-cutting by spark discharge-assisted diamond wire sawing. The setup is established based on a high speed WEDM machine (Fig. 1a). The workpiece is fixed on the workbench that moves on the X–Y plane with a constant feed rate set by the machine. The diamond wire is driven by a rotating roller of which the rotating speed can be adjusted by a frequency transformer. The

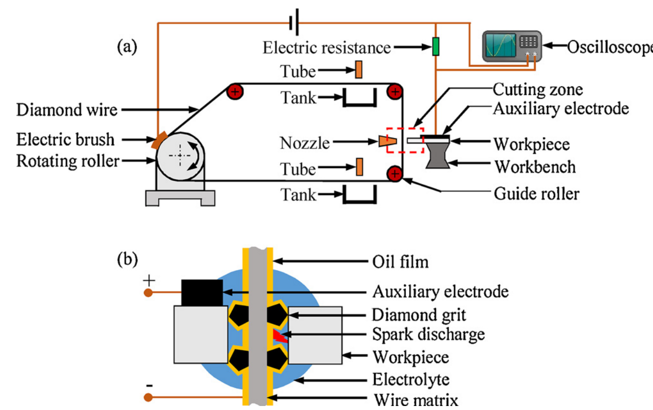

Fig. 1. Experimental setup of shape-cutting by spark discharge-assisted diamond wire sawing: (a) experimental setup; (b) enlarged view of the cutting zone.

diamond wire is connected to the negative pole of the DC power through the rotating roller and the electric brush. An auxiliary electrode is fixed on the workpiece. By using a nozzle, electrolyte is sprayed to the cutting zone to connect the diamond wire and the auxiliary electrode. The oil is supplied to the diamond wire by tubes, and the tanks are used to recycle the redundant oil. A 1Ω electric resistance is connected in series to the circuit and so the current of the circuit can be measured with an oscilloscope. The principle of the oil film assisted WECDM can be illustrated by the enlarged view of the cutting zone (Fig. 1b). It can be seen that the oil film isolates the diamond wire from the electrolyte. It is possible that the oil film is absent in some micro areas of the diamond wire, but the electrolysis will immediately generate hydrogen gas to patch the insulating film. When the DC voltage is applied to the diamond wire and the auxiliary electrode, an electric potential difference is formed on two sides of the oil film. As the DC voltage is higher than a certain value, spark discharges are generated around the diamond wire. The mechanism of material removal by electrochemical discharges can be explained according to the research by Jalali et al. [25] and Jain et al. [26].The heat provided by the spark discharges locally increases the temperature. Water in the vicinity of the machining zone is evaporated and only NaOH in the form of molten salt remains. Under the high temperature circumstance, the quartz glass is etched by OH radicals through the following reaction:

$$2NaOH + SiO_2 \rightarrow Na_2SiO_3 + H_2O \quad (1)$$

According to the above chemical reaction, the chemical etching products are Na_2SiO_3 and H_2O. The Na_2SiO_3 is removed by the electrolyte. In spark discharge-assisted diamond wire sawing, the Na_2SiO_3 can be immediately removed by the quickly moving diamond wire. The new exposed quartz glass continued to be etched to ensure continuous material removal.

2.2. Experimental materials and design

A 1.0 mm thick quartz glass (characteristics are shown in Table 1) was used. The material of the auxiliary electrode was graphite. The

Table 1
Characteristics of the quartz glass.

Parameters	Values
SiO_2 content	99.99%
Density (g/cm^3)	2.203
Hardness (Mohs, N/mm^2)	5.5-6.5
Electric resistance (Ω cm)	7×10^7
Softening point (°C)	1683
Thermal conductivity (W/°C m) (at 20 °C)	1.38