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Research paper

Cutting of hard and brittle insulating materials using spark discharge-assisted diamond wire sawing

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ABSTRACT

Hard and brittle insulating materials have good application prospects but are difficult to machine. This research focuses on the feasibility of cutting such materials using spark discharge-assisted diamond wire sawing. By the electrochemical discharge machining (ECDM) method, spark discharges are generated on the diamond wire. However, no spark discharge is produced when the thickness of workpiece is beyond 5.0 mm, because of the difficulty in generating hydrogen gas film to electrically insulate the diamond wire from the electrolyte. To solve this problem, an oil film is online coated on the diamond wire to separate it from the electrolyte. Oil film may be absent at some micro areas where electrochemical reaction occurs and hydrogen gas is generated. Consequently, an electrically insulating film, which consists of oil and hydrogen gas, is formed on the diamond wire. Experimental results show that evenly distributed spark discharges are generated during the cutting of a 36.0 mm thick workpiece. The combination of spark discharge and diamond wire sawing facilitates the spalling of hard and brittle insulating materials. The material removal rate (MRR) and surface roughness increase with the DC voltage, wire speed, and counterweight mass.

1. Introduction

Many hard and brittle insulating materials, such as glass, quartz, and several ceramics, have been widely used in recent high technology applications owning to their unique electronic, chemical, and physical characteristics (Yoshino et al., 2005). These materials are inevitably cut for use in mechanical structural parts. However, cutting such materials through conventional machining methods is difficult due to their hard and brittle characteristics. The wire electrical discharge machining (EDM) method is also unsuitable because of the insulating property of these materials.

Several researchers have attempted to develop efficient and accurate methods of machining hard and brittle insulating materials. Abrasive waterjet was used to cut silicate glass (Zhu et al., 2009) and alumina ceramic (Shanmugam et al., 2008), but the angle of the cutting surface is obvious and unavoidable in this method. Ultrasonic vibration was used in abrasive waterjet machining (Hou et al., 2017). The pulsation behavior of the abrasive waterjet was improved but not the machining accuracy. Laser technique was applied to cut a 1.0 mm thick alumina ceramic (Chen et al., 2012). However, its machining accuracy was restricted by the focus position. A laser-controlled fracture peeling technique was proposed to process alumina ceramic (Yan et al., 2013). This method is suitable for surface polishing but not for cutting. Plasma arc technique was used to cut insulating Si_3N_4 ceramic (Zhang et al., 2013). However, its machining accuracy was poor because focusing the plasma beam in air is difficult. The assisting electrode method was proposed to machine the insulating Si_3N_4 ceramic (Tani et al., 2004) and zirconia (Hou et al., 2014), but this method relies on the unstable and uncontrollable carbon layer generated by kerosene decomposition. Electrochemical discharge machining (ECDM) was used to cut a 2.0 mm thick non-conductive e-glass fiber epoxy composite (Malik and Manna, 2016), but its material removal rate (MRR) was low. When this method was applied to cut alumina ceramic, the MRR was only 0.06 mm^3/min and the thickness of the workpiece did not exceed 2.0 mm (Peng and Liao, 2004). Free abrasive wire cutting method was used to cut monocrystalline silicon (Bidiville et al., 2015). However, the MRR was only approximately 0.9 mm^3/min when alumina ceramic was cut. Diamond wire sawing has a better MRR than the free abrasive wire cutting method because the diamond grits are fixed on the wire (Clark et al., 2003). Nevertheless, the MRR should be improved due to the increasing demand for hard and brittle insulating material parts. The diamond wire sawing device was optimized (Turchetta et al., 2017), but only the accuracy of the machined parts was improved.

Hybrid manufacturing processes provide solutions for machining hard and brittle materials. The combination of electrochemical machining (ECM) and grinding was developed for processing conductive

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hard-to-machine materials to achieve a high-efficient and burr-free material removal process (Lauwers et al., 2014). During the ECM grinding of ceramic–metal tungsten, tungsten is dissolved through electrochemical reaction, which facilitates abrasive micro cutting (Mogilnikov et al., 2013). To continue with ECM, a metal rod with coated diamond abrasives rotates and is fed down to remove the soft and non-reactive passivation layer (Zhu et al., 2011). Consequently, burr-free precision holes with sharp edges are obtained. The abrasive electrochemical method based on a multi-wire saw system was proposed to slice solar silicon (Wang et al., 2011). The work material is oxidized by electrochemical reaction and subsequently removed by abrasion. Surface integrity is improved and the MRR is increased with this method.

EDM was integrated with grinding to machine hard but conductive materials. During EDM grinding of cemented carbides with metal bonded diamond grinding wheels, the grinding performance is enhanced by both effectively removing material from the workpiece and declogging the grinding wheel surface (Koshy et al., 1997). The surface textures show the decrease of the role of the grinding process with an increase of the current on the workpiece side. Spark discharges also soften the material in the grinding zone thermally, consequently decreasing the cutting force and the required spindle power (Koshy et al., 1996). During the abrasive-wire-EDM of Ni-based alloys with a diamond wire, material removal due to grinding increases with the decreasing voltage and current (Menzies and Koshy, 2008). The surface presents an abrasion topography when voltage and current decrease to 108 V and 8 A, respectively. Investigations on the electrical discharge diamond face surface grinding of aluminum oxide and boron carbide ($Al/Al_2O_3p/B4Cp$) were conducted (Yadav and Yadava, 2017), and results showed that the MRR and surface roughness increased with the increasing current, wheel rotational speed, and feed rate that is parallel to the machined surface, but decreased with the reduction of grit size.

ECM and EDM grinding are not applicable for machining non-conductive materials. Thus, the method of combining ECDM and grinding was proposed. The machining accuracy and surface roughness of wire-ECDM were improved with the addition of SiC grits to the electrolyte (Yang et al., 2006). However, the MRR increase was limited because the free SiC grits cannot provide sufficient cutting force and have a negative effect on the stability of the hydrogen gas film, resulting in unstable spark discharges. During the ECDM grinding of holes on borosilicate glass and alumina with DC power (Jain et al., 2002), abrasive particles embedded rotary tool (cathode) serves as a grinding wheel. The abrasive particles can avoid physical contact between the metal matrix of the wheel and the workpiece, which facilitates the ECDM process. The MRR increases with the voltage exerted on the tool and the auxiliary electrode. The machined surface of borosilicate glass exhibits abrasion and thermal removal, whereas the produced surface of alumina only presents abrasion removal. The use of pulse DC power improves surface quality and saves energy in ECDM grinding of holes (Chak and Rao, 2007).

The research focus is the feasibility of cutting hard and brittle insulating materials using spark discharge-assisted diamond wire sawing. The generation of spark discharges was investigated. In addition, the effects of applied DC voltage, wire speed, and counterweight mass on MRR and surface roughness were analyzed.

2. Diamond wire sawing setup

Fig. 1 shows the schematic of the diamond wire sawing setup used in this research. The rotating roller drives the movement of the diamond wire, and the workpiece is fixed on the slider that can move freely on the guide. The slider is pulled by a counterweight and moves forward with the removal of work material. With this feed mode, the workpiece feeds only when the work material is removed. The feed rate of the workpiece is not a process parameter, but a result of work material removal.

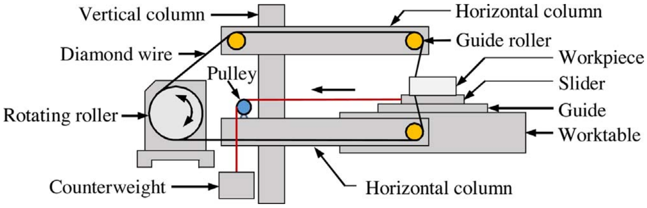

Fig. 1. Schematic of the diamond wire sawing setup.

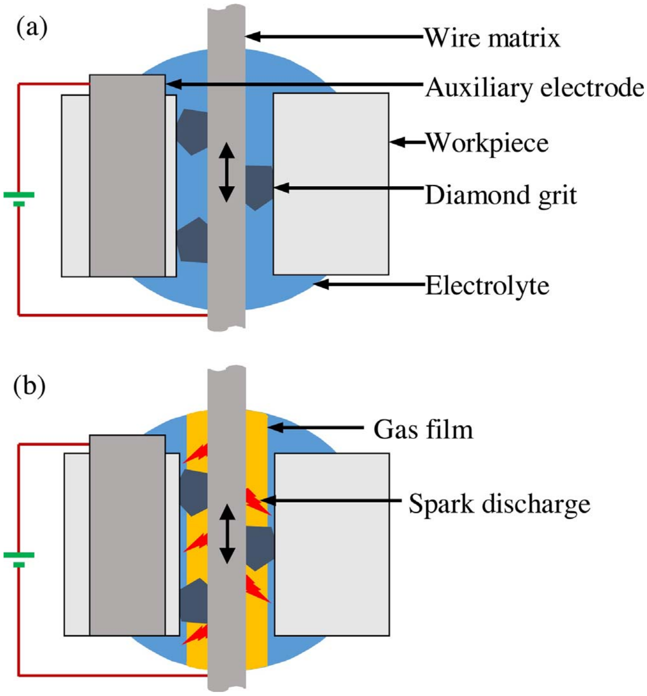

Fig. 2. Principle of spark discharge generation by ECDM process during diamond wire sawing: (a) Without the application of DC voltage, (b) With the application of DC voltage higher than the critical value.

3. Spark discharge generation during diamond wire sawing

3.1. ECDM process

Fig. 2 shows the principle of spark discharge generation by ECDM process during diamond wire sawing. The diamond wire and the L-shaped auxiliary electrode are connected to the negative and positive poles of the DC power, respectively (Fig. 2a). Electrolyte is sprayed into the cutting slit using a nozzle to connect the diamond wire and the auxiliary electrode to generate a circuit. When the applied DC voltage is low, electrochemical reaction occurs and hydrogen gas is generated on the diamond wire. As the voltage continuously increases, more hydrogen gas is produced to finally form a gas film around the diamond wire. The film electrically insulates the diamond wire from the electrolyte. Consequently, nearly the entire voltage applied by the DC power is exerted on the diamond wire and electrolyte. When the voltage exceeds the critical value (Fascio et al., 2004), spark discharges occur within the film (Fig. 2b). The spark discharges momentarily increase the temperature and reduce the strength of the work material, thereby improving the material removal through the moving diamond wire.

Experiments were conducted to verify the capability of spark discharge generation by ECDM during diamond wire sawing. A glass material (characteristics are shown in Table 1) was used as the workpiece to observe the phenomenon in the cutting slit. The diamond wire was fixed on the rotating metal roller that was connected to the negative pole of the DC power through an electric brush. The material of auxiliary electrode was stainless steel. A NaCl solution with a mass