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Experimental investigation of spark generation in electrochemical discharge machining of non-conducting materials

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ABSTRACT

Electrochemical discharge machining (ECDM), also known as spark assisted chemical engraving (SACE), is an effective micro-machining process for non-conducting materials. Process modeling of ECDM, including spark generation and material removal, is not fully established however. Empirical estimation for discharge energy results in large prediction error of material removal and is hard to experimentally validate. In this paper, an experiment-based stochastic model for spark energy estimation is presented. Tapered tool electrodes were fabricated by electrochemical machining (ECM) to improve the consistency of spark generation. Energy of sparks was experimentally determined and fit into a two-component mixture log-normal distribution to reveal electrochemical characteristics of tool electrodes. A finite element based model was established to correlate spark energy and the geometry of removed material. Material removal was treated as heat transfer problem because electrical energy released by spark generation transfers into thermal energy on the workpiece, resulting in material removal due to thermal melting and chemical etching. Predictions of material removal by the model demonstrated good consistency with experimental results.

1. Introduction

The demand of non-conductive material has grown rapidly with the broad application in optical, electrical, and mechanical systems. Glass is expansively employed due to the properties including optical transparency, high stiffness, and good chemical resistance. Electrochemical discharge machining (ECDM), taking advantage of electrochemical discharge phenomenon, is a non-traditional micro machining process. Non-conducting materials can be machined by ECDM by employing auxiliary electrodes. This process is also known as spark assisted chemical engraving (SACE). Features with high aspect ratio and complicated geometry can be created by ECDM (Zheng et al., 2007).

Improving the machining efficiency and quality has long been the concentration for studies of ECDM of non-conducting materials. To achieve a better machining process, innovative methods were introduced into conventional ECDM, including developing new procedures and machining tools. Wuthrich and Hof (2006) applied tool vibration and experimentally demonstrated the increment in the material removal rate. Yang et al. (2011) fabricated a spherical tool electrode and showed the merits of the new tool with respect to machining efficiency and accuracy. Mochimaru et al. (2012) introduced a two-step machining method to reduce the over-cutting in drilling process.

Conventional ECDM, as the fundamental of all innovative machining techniques, is not fully revealed and optimized. The machining quality by ECDM is sensitive to many process parameters. However, it is unclear that which of the parameters affect the machining quality and how these parameters can be optimized (Wuthrich and Fascio, 2005). Process modeling is an important approach of understanding the mechanism of ECDM. Studies of process modeling involve discharge phenomenon, gas film formation, and material removal (Wuthrich, 2009). Basak and Ghosh (1996) estimated the material removal rate by evaluating energy, and frequency of spark generation (Basak and Ghosh, 1997). Jalali et al. (2009) quantitatively characterized material removal due to thermal heating and chemical etching and estimated the machining temperature. Finite element analysis was widely employed in modeling. Jain et al. (1999) developed a finite element based heat transfer model to estimate the thermal effects of single spark. Bhondwe et al. (2006) established a finite element model to predict material removal rate.

Experimental verification for process modeling of ECDM, however, is often indirect and inaccurate. There are various reasons that results in such difficulty. First, the discharging and material removal process is very sensitive and is vulnerable to changes in ambient condition, which caused low repeatability in experiments. Second,

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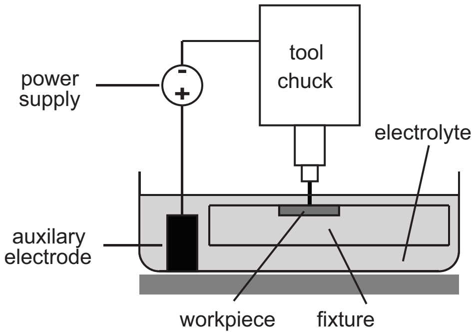

Fig. 1. Experimental setup of ECDM.

real-time observation is not feasible for micro-scale machining, especially in high temperature alkali solution. Sensors installed in the machining area could interfere with the original setup and thus change the electrochemical and fluid dynamic characteristics of the process.

In this paper, process modeling for spark generation and material removal is presented. Spark energy was experimentally determined and fit into a stochastic model. A tapered tool electrode was fabricated and employed in the experiments to increase the consistency of spark generation. A finite element model was developed to correlate spark energy to material removal. Experiments were delivered to validate the models.

2. Experiment preparation

An experimental setup was designed and fabricated to implement ECDM (Fig. 1). A machining chamber consists of chemicals was fixed to a CNC machine, with the tool electrode clamped on the machine. The power supply could provide DC or pulse output from 0 to 64 V in the range of 0–10 A current. Electrode voltage directly affects the machining efficiency. If the electrode voltage is too high, thermal cracks tend to happen (Wuthrich et al., 2006), while a minimum voltage must be maintained to ignite the electrochemical reaction (Maillard et al., 2007). In most of the works presented in this paper, the output was set to be 34 V if not specifically noticed. The workpiece was a sheet of soda-lime glass with 1 mm thickness, which consisted of 74 wt.% SiO_2, 13 wt.% Na_2O, 10.5 wt.% CaO.

The process characteristics of ECDM are closely related to the properties of tool electrode (Mousa et al., 2009). Cylindrical tools, as are conventionally used in ECDM process, do not have desired electrochemical characteristics in the study of discharging activity. Fig. 2 is the picture of a crater created by ECDM process using a 0.5 mm diameter cylindrical tool with the discharging duration of 2 s. Fig. 2 illustrates that material near the rim of the cylindrical tool was removed, indicating release of sparks were distributed around the rim, or “fringing effect”. By replacing the cylindrical tool with a tapered end tool, however, could make discharges focus on a concentrated region.

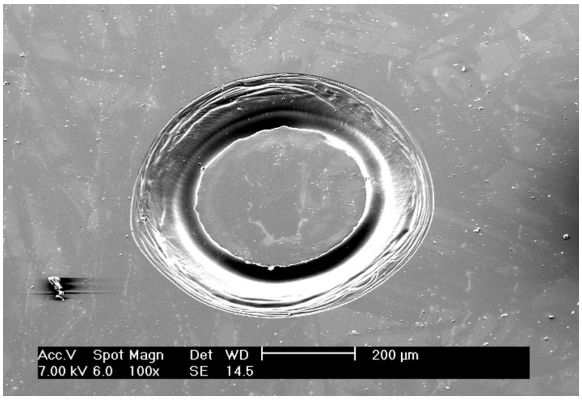

Fig. 2. Crater created by a cylindrical tool electrode. Machined with 35 V electrode voltage and 2 s machining time.

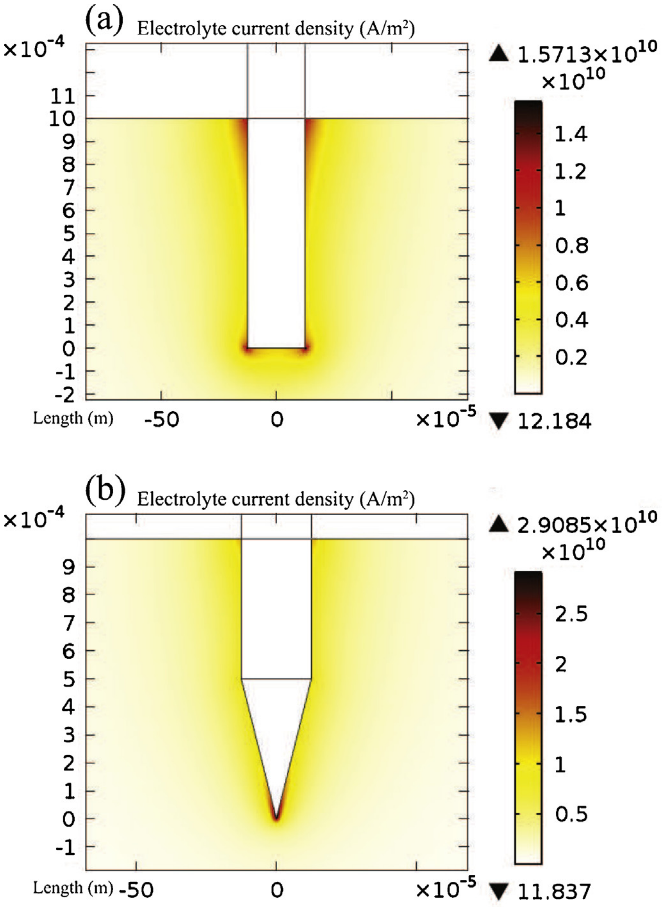

Fig. 3. Finite element simulation of current density in electrochemical reaction. (a) Cylindrical electrode. (b) Tapered electrode.

A finite element simulation was deployed to investigate electrochemical reaction in the machining process. Tool electrode was chosen to be tungsten with 250 μm diameter and the electrolyte was 30 wt.% NaOH. Electrode voltage was set to 30 V. The simulation proved that fringing effect existed for cylindrical tools, while tapered tool has only one spot for spark generation. Fig. 3 shows the current density around the tool electrodes (brighter color represents higher current density). It can be seen that current density is more intense near the rim for cylindrical tools. Thus, sparks tend to generate from any point along the rim of the tool electrode, if not considering and geometrical defects. However, sparks can only be generated at the tip of tapered tools, and thus increased consistency in spark generation.

Electrochemical machining (ECM) was facilitated to fabricate tools with tapered end (Fig. 4). Tapered tools were made from tungsten rods with 250 μm diameter. The rods were cut to approximately one inch long and clamped on the chuck. Tool and chuck were connected to the power supply as the anode in ECM process. The auxiliary electrode was made of stainless steel. A hole was drilled on the center of auxiliary electrode, surrounding the tool electrode to create an axisymmetric electrical field in the electrochemical reaction. The auxiliary electrode was immersed 1 mm under the upper surface of the electrolyte (8 wt.% NaOH).