International Journal of Machine Tools & Manufacture 73 (2013) 47–54

Contents lists available at SciVerse ScienceDirect

International Journal of Machine Tools & Manufacture

journal homepage: www.elsevier.com/locate/ijmactool

Forces exerted on the tool-electrode during constant-feed glass micro-drilling by spark assisted chemical engraving

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ARTICLE INFO

Article history:
Received 29 November 2012
Received in revised form
20 June 2013
Accepted 24 June 2013
Available online 1 July 2013

Keywords:
SACE
ECDM
Glass micro-drilling
Force measurement

ABSTRACT

The forces exerted on the tool-electrode during Spark Assisted Chemical Engraving (SACE) constant velocity-feed glass micro-drilling are measured for different machining voltages, tool feed-rates and tool sizes. A diagram of the force regions in the hole-depth vs. tool feed-rate plane is constructed for different voltages and tool sizes. Two rate limiting steps for micro-drilling were identified. For low depths, the rate limiting step is the work-piece surface heating while for high depths it is the electrolyte flushing. Based on these findings, the tool feed-rate vs. hole-depth plane of the force regions was normalized using the time needed to heat the local glass surface and the tool radius. A correlation between the force occurrence and the current signal is identified where the current shifts upwards by a constant value when a force is exerted on the tool. This finding allows the usage of the current signal to detect the contact between the tool and the glass surface. The measurement and understanding of the forces exerted on the tool-electrode that this work brings is a first step towards the development of force feed-back algorithms for SACE machining.

1. Introduction

Spark Assisted Chemical Engraving (SACE), known as well in the literature under the names Electro Chemical Discharge Machining (ECDM) and Electro Chemical Spark Machining (ECSM), is one among a number of glass micro-machining technologies. This non-traditional technology, is based on electro-chemical discharge phenomena [1,2]. Machining occurs due to thermal assisted etching [3–10]. The heat provided by the electrochemical discharges allows the temperature to reach about 500–600 °C in the machining zone [11–14]. This accelerates etching of the work-piece by means of the OH radicals supplied from the electrolytic solution in the electrochemical cell based on the following reaction [6,9,11]

$$2x\mathrm{NaOH}+x\mathrm{SiO_2}\rightarrow x\mathrm{Na_2\,SiO_3}+x\mathrm{H_2O} \quad (1)$$

During machining, the product of reaction (1) is evacuated out of the machining zone by the flowing electrolyte. As the temperature in the machining zone reaches the glass transition temperature, a glass layer of reduced viscosity forms below the tool. This layer will be referred to as “glass melt” in this text. The formation of such a layer was already reported in the case of 2D glass machining by SACE [15].

So far, several successful studies about minimization of geometrical errors of machined surfaces were reported in case of drilling and machining 2.5D structures with SACE [16–18]. However, the process is still blind machining due to the lack of a suitable feedback signal to give sufficient information about the machining status. Further, like other micro-machining technologies such as micro Electrical Discharge Machining (μ-EDM) and micro Electro Chemical Machining (μ-ECM), SACE faces the problem of flushing the machining spot in case of micro-drilling. Contrary to μ-EDM and μ-ECM, which use the gap voltage or current signal to monitor the tool-work piece gap in order to optimize material removal [19–21], the last could not yet be achieved in SACE machining. As a result, the most popular SACE drilling strategy is gravity-feed drilling. In addition to inadequate flushing of the machining spot, this approach suffers from tool bending, where both are serious problems especially when using micro-tools [22].

Although the current signal proved to be useful for extracting information about the machining process [23], the feasibility of using it as a feedback signal is still to be demonstrated. In this paper, an alternative signal to potentially develop feedback algorithms is explored: the force exerted on the tool during micro-drilling. No knowledge regarding this signal is available as of today. It is the first time that the forces are measured and analyzed to extract information related to the machining process. The possibility of using the force as a feedback signal to monitor the SACE machining process is discussed. In addition, it is shown that the current signal can be used to detect the tool work-piece

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http://dx.doi.org/10.1016/j.ijmachtools.2013.06.008

contact. This opens new possibilities to use the current signal to develop feedback algorithms for SACE machining.

2. Experimental setup

The apparatus is composed of a machining head and a processing cell (Fig. 1). The machining head, mounted on the *Z*-axis of a Cartesian robot, is composed of a flexible structure that can move freely in the *z*-direction parallel to the *Z*-axis, adding up a degree of freedom to the system. The machining head can be either used as a force sensor or as a profile-meter. The force sensor mode is obtained by using the zero-displacement force measurement principle. A PID controller maintains a fixed z position (measured with an optical sensor) by driving a voice coil actuator fixed on the flexible structure. The force needed to maintain a fixed z position is equal to the force exerted on the tool-electrode during machining. The PID controller was implemented using a dSPACE 1104 controller board. The force sensor has 100 ms response time to disturbance, an operating range of 0 to 5 N with 10 mN rms noise. In case the voice coil actuator is not driven (i.e. switched off), the machining head can be used as a profile-meter. The processing cell, in which the glass work-piece is fixed, is mounted on the XY stage to align the tool-electrode and the work-piece. An overflow system is used to maintain a fixed level of electrolyte above the work-piece (about 1 mm).

To study the forces exerted on the tool-electrode during micro-hole drilling, a set of experiments was conducted using different machining voltages (30 and 33 V), a range of tool feed-rates (1–80 μm/s) and two tool sizes (250 and 500 μm in diameter). The tool-electrodes are stainless steel (316 L) cylinders. The electrolyte is 30 wt% NaOH and the work-pieces are soda lime glass microscope slides (Bio Nuclear Diagnostics Inc.).

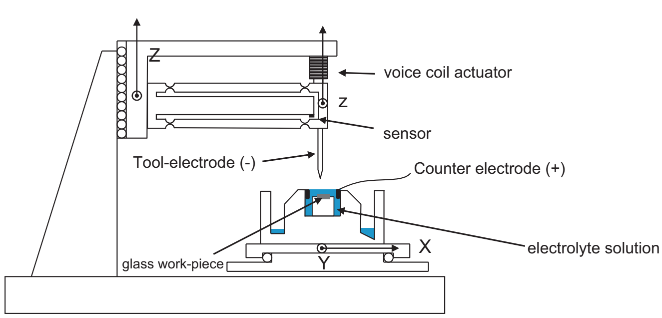

Fig. 1. Schematic of SACE mechanical set-up which includes the machine head (holding the tool-electrode) mounted on a Z-stage and the cell (containing the glass slide) mounted on an XY stage. The machine head is composed of a flexible structure, to which the tool-electrode is attached, that can move freely in the *z*-direction. When used as a force sensor, a voice coil linear actuator is controlled to hold the structure at a fixed z position, measured by an optical sensor.

Prior to machining, the tool is positioned 50 μm above the glass surface (using the profile-meter function of the machining head). The machining voltage is switched on for 5 s in order to preheat the tool and the machining head is switched to the force sensor mode. Machining proceeds subsequently by moving the tool towards the glass at the specified feed-rate while recording the force signal. The holes machined were 250–400 μm deep. For each set of experiments 50 holes were produced to enhance the analysis reliability. Data was acquired using the ControlDesk software.

3. Results and discussion

3.1. *Types of forces*

Based on the experimental results, three distinct force patterns are distinguished as depicted in Fig. 2. In the first configuration, the force signal increases linearly and saturates exponentially before dropping abruptly. In the second configuration, the force increases as in the first one, but then grows linearly further before dropping. In the third configuration, the forces increase linearly only. Based on the current understanding of the machining behavior, the following interpretation is proposed.

When no contact exists between the tool and the glass surface, no forces are present. As the tool touches the work-piece surface (Fig. 2a), a force appears. In the first configuration, the force increases and then grows at a reduced rate before recovering. A mechanism contributing to this force pattern is the on-going machining below the tool tip while the tool is pressing on the glass surface. These forces appear mainly near the work-piece surface in case of machining at high voltage (quicker surface heating). Note that in this configuration the forces lasted for a few microns before they disappeared abruptly due to the fast etching of the heated glass layer.

In the second configuration the force grows at a reduced rate, in a similar manner to the first one, depicting the on-going etching. However, afterwards the force increases again linearly, during a short time, before recovering. This increase is attributed to the low machining rate (dropping to almost zero) where for this case the slope of the force signal depicts the mechanical stiffness of the setup. This configuration was most often observed at depths higher than 100 μm where flushing is more difficult.

The third configuration (Fig. 2c) occurs either at the surface of the work-piece, when machining at both low voltage and high feed-rates, or at high depths. For low machining voltage the local machining zone is not hot enough to allow fast etching. Further, for high drilling depths (which vary depending on the tool feed-rate and the machining voltage; see Section 3.2), the material removal rate decreases significantly due to the lack of electrolyte supply inside the hole. In this case, the tool is always pushing on the glass surface and the forces are not recoverable. The

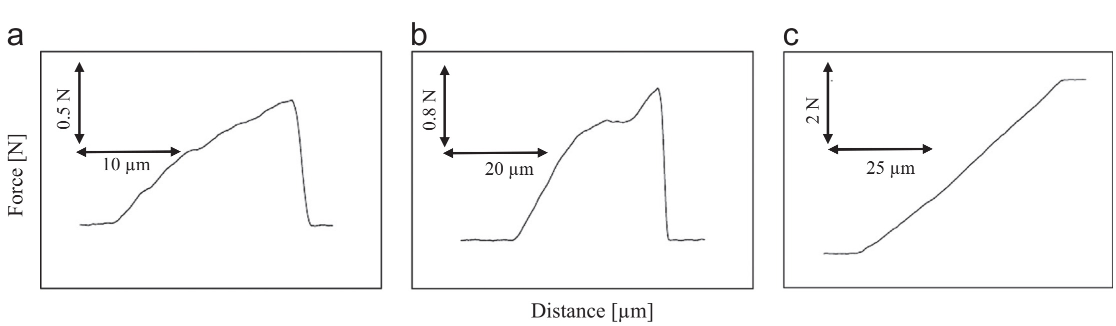

Fig. 2. The three force patterns resulting from (a) on-going machining while the tool contacts the glass (recoverable force), (b) on-going machining with glass surface contact followed by negligible etching (recoverable force) and (c) negligible etching (unrecoverable force).