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Flow-jet-assisted electrochemical discharge machining for quartz glass based on machine vision

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ABSTRACT

A vision-sensor-based system used for on-line characterization and monitoring of the effect of flow-jet-assisted electrochemical discharge micro-drilling on quartz glass is proposed. The feasibility of electrochemical discharge machining with an assisting flow jet on nonconductive quartz glass materials was explored in this work. Through in-situ image acquisition and analysis of the electrochemical discharge drilling processes, associations between the drilling performance and analyzed images could be obtained promptly. Hence, the penetration status of electrochemical discharge drilled holes could be estimated efficiently in real time using a vision sensing method for the on-line detection of sparks. The influence of the flow jet on material removal and crater depth formation is reported, and the influences of the assisted flow on the machining efficiency of the drilled holes are examined. The results showed that the machining efficiency of the electrochemical discharge-drilled holes were correlated to the drilling rate per accumulated pixels with a high degree of confidence. The penetration time and outlet diameter were adopted as the response parameters for controlling the drilling process. A novel machine-vision-based method for feedback control and for monitoring the status of electrochemical-discharge-drilled holes in real time is proposed in this research.

1. Introduction

Glass applications have the benefits of great isolation properties, thermal compensation, optical transparency, and mechanical strength of the material. The traditional mechanical drilling of glass is known to produce cracks and chipping at the exits of holes on the workpiece, and machined surfaces are normally rough owing to deformations imposed by the thrust force incurred during drilling [1]. The challenge with glass micromachining is tied to the hardness and brittleness of the material. For insulating materials, unconventional processes are chosen to achieve economical hole drilling. The machining of insulating materials in a non-contact thermal machining process is associated with challenges [2]. Electrochemical discharge machining (ECDM), also known as spark-assisted chemical engraving (SACE), is one such unconventional drilling method, and possesses all of the capabilities needed to meet the demands of machining tiny and micro-sized holes in glass [3,4]. ECDM is an unconventional material removal process that melts or vaporizes the workpiece by using the thermal energy. This is accomplished by using high temperature spark discharges that are induced within a bubble layer that surrounds the tool electrode contour. As soon as the potential difference between the electrodes exceeds a threshold voltage, the repetitive spark discharges between the electrolyte and the tool electrode [5]. Regarding equipment costs, ECDM is relatively inexpensive when compared to other machining techniques such as those involving ultra-short lasers [6], wet-etching technology [7], and deep plasma etching [8]. ECDM is appropriate for drilling glass materials where high surface quality and accuracy are required. However, the reliability of ECDM drilling with glass is low; the machined smoother surfaces and relatively cheap equipment expenses make it an excellent choice for industrial applications [9]. A survey of the literature has shown that many attempts have been made to improve the machining performance of ECDM. Wüthrich et al. [10] presented an experimental technique for inspecting the thickness of a bubble layer by analyzing the current-voltage characteristics of the machining process. The method demonstrated that significantly higher machining repeatability could be achieved by reducing the gas film thickness, affecting the wettability on the tool electrode. In 2007, Zheng et al. [11] increased the gap distance between the tool sidewall and the drilled hole by changing the geometry of an electrode to a flat sidewall-flat front shape. This was intended to decrease the effect of the discharge around the tool sidewall and improve the circulation of the electrolyte within the microhole, which would in turn enhance the drilling performance

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and accuracy. In [9], Cheng et al. revealed that the stability of the bubble layer formation determined the accuracy of the machine, its surface roughness, and the reproducibility of the machined parts. This indicated that there was a certain relationship between the current signal and the quality of the gas film. As the processing depth deepens, machining efficiency was reduced due to the lack supplement of circulation of the tip electrolyte, and the average current value tends to increase. Han et al. [12] improved the machining depth of the ECDM drilling process by using ultrasonic electrolyte vibration and adequate electrolyte flow to preserve the steady spark generation. Laio et al. [13] revealed that adding a surfactant to the electrolyte was effective in inducing more machining spark energy and for promoting machining speed. Goud et al. [14] reviewed the machining parameters of the electrochemical discharge drilling on the material removal rate and categorized the main parameters that affected ECDM performance. These included the tool electrode, electrolyte, power supply, and workpiece materials. Wüthrich et al. [15] presented the potential of closed-loop feedback control based on the current signal, which contained information on spark production to examine the drilling process. Mochimaru et al. [16] reported a feedback circuit that automatically terminated the machining process when the microtool electrode penetrated the workpiece.

With the increasing complexity of the ECDM drilling processes and the extended drilling time needed to produce multiple holes as well as the importance of the accurate and precise requirements in-process and on-machine feedback control becomes necessary. These control schemes are needed to eliminate the influences of disturbances in the drilling process and to compensate for fluctuating parameters caused by unstable gas films, which lead to low machining repeatability [10]. The available literature mostly addresses the qualitative study of the ECDM applications and its process [17]. Nevertheless, no significant work is available in the literature that has addressed the feedback control of the process for ECDM drilling. The ECDM machining process is still blind machining as there is a lack of an appropriate feedback control mechanism to provide an adequate signal regarding the machining status [18]. In addition, an active control of the process is needed to further improve the drilling characteristics of ECDM. To overcome the restrictions encountered while machining quartz glass using an ECDM process, the present study innovatively proposed using a flow jet and machine vision to characterize the influence of drilling parameters and their relations on the quality of the holes machined during the ECDM process. This has opened new possibilities for the utilization of the vision signal to develop feedback capabilities for ECDM. The penetration time of nonconductive quartz glass materials was used as the response parameter to evaluate the drilling performances.

2. Materials and methods

A spring-fed needle tapered tool (outer diameter: Φ 404 μm and the tip size is 77 μm) was used as the electrode to drill holes on quartz glass. The intention behind its use was to demonstrate an improvement over gravity-fed tool configurations. Needle-shaped tools yield better machining performance due to the fact that concentrated discharges are mainly produced around the tip of the tool electrode [14,19]. Compared to gravity-fed tool electrodes, machining improvements can be achieved by adopting a spring-fed tool electrode in a vertical feed motion. The frontal gap always maintains contact by applying the continual feeding of the tool electrode toward the workpiece. During the ECDM process, when DC power or a pulsed voltage is provided between two electrodes, electrolysis happens at low potential. This results in the formation of hydrogen bubbles around the tool electrode and oxygen bubbles at the counter electrode. Bubble formation increases as the applied potential increases, and a gas film appears around the tool electrode as the bubbles begin to coalesce. Spark discharges occur because of the insulation breakdown of the hydrogen bubble layer as soon as the potential between the electrodes exceeds a threshold potential. According to [20], the gas film is the key influence that affects spark discharge, and the quality of drilling accomplished by the spark discharge is essentially controlled by the gas film quality during the ECDM process. In this work, a machine-vision-based signal to potentially develop feedback control was explored; this involved the incorporation of a flow jet nozzle on the tool electrode during microdrilling. This was the first time that vision signals were acquired and analyzed to extract useful data related to the ECDM process. The possibilities associated with using the vision sensor as a feedback signal to control the ECDM process are discussed. The experimental setup, which includes the ECDM system, power supply, image acquisition unit, jet nozzle, and computer analysis and control system, is shown in Fig. 1. All the experiments in this work are conducted using this system. The main elements of the system include the following: (I) spring-fed electrode assembly, (II) electrode clamp and assist nozzle unit, (III) camera acquisition unit, and (IV) DC power supply with a current/voltage detection unit. Each experiment was conducted three times, and the average values of the response measurements were adopted for analysis purposes. The entire experimental setup was built on a Micro Precision electro discharge machine (Sodick AP1L). A tungsten carbide tool-electrode was positioned vertically and fed along the depth axis in the electrolyte for microdrilling. The electrolyte fluid can be continuously and steadily supplied to the drilling zone via the interior of the assist nozzle. The electrolyte fluid was filled in the reservoir tank and the tool electrode was immersed within the electrolyte fluid. The DC power supply provided energy for the entire drilling process and was used to record the machining voltage and current data. The drilling voltage and current were recorded simultaneously by the DC power analyzer, thus the drilling process could be successfully analyzed in a timely manner during each experimental run.

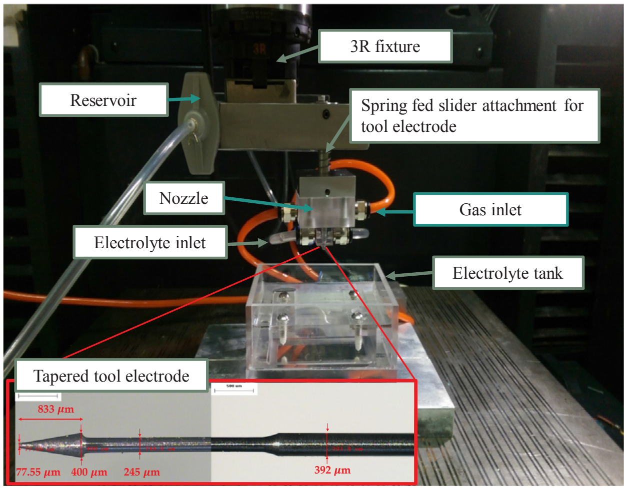

Fig. 1. Experimental setup and needle-tapered tool electrode.

2.1. Spring-fed electrode

During the machining of the quartz glass, the spring-fed tool electrode was pre-pressured on the quartz glass surface to feed the electrode that was in contact with the machining surface of the quartz glass. The influence of the spring-fed electrode pre-pressure on the surface strain of the test piece was calculated in combination with a digital image correlation method.

In order to investigate the stress induced by pre-pressure of the pressure spring, the digital image correlation (DIC) was employed to directly measure the deformation on the surface of interest. In order to perform the DIC, images composed of a random speckle pattern on the surface of the glass were acquired, and subsequently the local displacements at the surface of the glass were calculated. A speckle pattern