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Analytical and experimental study on the integration of ultrasonically vibrated tool into the micro electro-chemical discharge drilling

S. Elhami, M.R. Razfar*

Department of Mechanical Engineering, Amirkabir University of Technology, 424, Hafez Ave, Tehran, Iran

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ABSTRACT

Electrochemical discharge machining (ECDM) is a non-traditional machining process which is used to create micro-features on non-conductive materials. Micro holes and micro channels are the most interested features that have been fabricated by researchers. In recent years, some technical augmentations have been added to the ECDM process to achieve a more efficient machining process, but the employment of each augmentation in the most efficient way is not subjected. In this research, ultrasonic vibration is concentrated on the tool tip which directly and continuously effects on the machining zone and avoids global undesirable effects. For this purpose, modal analysis is used to design a special configuration which achieves the maximum amplitude of vibration in the tool tip. Also, an analytical model is presented for both of the electro-chemical discharge machining (ECDM) and ultrasonic assisted electro-chemical discharge machining (UAECDM) to study the effect of ultrasonic vibration on the thickness of gas film. Practical gas film thickness, machining speed, entrance overcut and tapering zone are studied for both of the ECDM and UAECDM to comprehensive understanding the effect of integration of ultrasonic vibration into the traditional ECDM process. Captures of gas film in different condition confirmed that ultrasonic vibration has reduced the thickness of gas film. Same behavior was achieved by employment of the analytical modeling. As a result, numerous small discharges were achieved which increased the material removal rate (MRR) and hole accuracy, simultaneously. Results showed that ultrasonic vibration can increase MRR up to 82%. Also, tapering zone and entrance overcut deviation as accuracy parameters improved 50% and 40%, respectively.

1. Introduction

Glass is a non-crystalline amorphous solid which provides special properties and applications. Glass presents acceptable thermal and chemical resistance in high temperature or corrosive environments. Transparency is one of the more important properties of glass which extends its applications in optic industries. The unique properties of glass attracts attention of advanced industries to implement this material in the fabrication of micro pumps, micro reactors, micro fuel cells [1], micro fluidic devices and several biomedical devices [2], but this special material has some constraints which limit fabrication processes. Hardness and brittleness of glass lead to poor machinability, so shaping of the glass workpiece is a major limitation.

Some manufacturing processes implement mechanical and thermal mechanisms to shape the glass parts. Ultrasonic machining (USM) [3] and abrasive water jet machining (AJM) are the most important processes that use mechanical mechanism to remove the materials and can be applied to non-conductive workpiece [4], but these processes have low machining speed and cannot fabricate features on ductile materials.

Laser beam machining (LBM) is the major process that uses concentrated thermal source to shape the desirable features. Extensive equipment and great electrical energy require to make a laser beam. Concentrated heat source leads to more heat affected zone (HAZ) and micro cracks which are undesirable events for industrial applications [5]. Electric discharge machining (EDM) is another manufacturing process which is used thermal mechanism by the application of electrical discharges [6], but this efficient process cannot be used for non-conductive materials. So, there is a need to utilize a machining method that reduces disadvantages and sustains capabilities of mentioned processes.

ECDM is an advanced machining processes which can be used to machine non-conductive, hard and brittle materials with low

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* Corresponding author.
E-mail addresses: Elhami@aut.ac.ir, Sadegh.elhami@gmail.com (S. Elhami), Razfar@aut.ac.ir (M.R. Razfar).

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cost and acceptable efficiency. Kura Fuji in 1968 introduced this machining process and their capabilities [7].

ECDM experimental configuration consists of two electrodes with different sizes. Cathode is much smaller than the anode. Anode completely is immersed in the electrolyte while cathode is immersed few millimeters (1…3 mm). DC electric current is applied on electrodes and gravity feed mechanism position the glass workpiece close to cathode [8].

ECDM is a combination of electrochemical, discharge and chemical phenomena. Electrolysis is a type of electrochemical phenomena which produces hydrogen bubbles around the cathode. Small size of cathode, in comparison to the anode, leads to coalesce of hydrogen bubbles and the formation of gas film which plays an important role in the efficiency and accuracy of ECDM process. Completed gas film insulates the tool from the electrolyte while electric power is applied, so electric discharge takes places. Positioning of the workpiece close to the tool causes to transfer some portion of discharge power to the workpiece. Transferred power melts and vaporizes a small part of the workpiece. Many discharges make significant material removal and have a noticeable contribution on the final MRR. On the other hand, a small portion of MRR is made by the chemical mechanism between the electrolyte and glass [9].

Improvement the efficiency of ECDM process is main target of many researches. So, researchers implement mechanical, chemical and some other physical phenomena to achieve a more efficient process. Unfortunately, many researches only study the MRR and did not pay attention to the accuracy of produced features [10].

Hajian et al. utilized two magnetic field configurations inside the electrolyte to fabricate a micro channel on the glass. Results showed that the direction of bubbles movement dependents on the magnetic field orientation. The most effect of the magnetic field was observed in low electrolyte concentration (15%) and high voltage (35 V) which produced smoother surface and a deeper channel [11].

Modification of electrolyte composition is another solution to achieve a more efficient process. Han et al. added graphite as conductive (electrical and thermal) powder to the electrolyte and observed the reduction of surface roughness from 4.86 to 1.44 μm. Results showed graphite particles changed discharge pattern and broke single discharge to two or three smaller discharges. So, breakdown voltage and surface roughness were reduced [12]. Chak et al. used abrasive particles of diamond whereas adhered to the surface of the cylindrical tool. Application of abrasive particles added the mechanical mechanism of cutting to the other mechanisms of the ECDM process, so the deeper hole was machined. On the other hand, diamond particles are insulated electrically, so improved the overcut as an important parameter of hole accuracy [13].

Tool movement is another method which can be used to improve the efficiency of ECDM process. Different types of vibration can be applied to the tool, electrolyte and workpiece. Low frequency vibration mainly effects on electrolyte circulation in the hole. In other words, this type of vibration flushes electrolyte to the hole, so in hydrodynamic regime MRR increases significantly. This type of vibration does not change the nature of physical and chemical phenomena in the ECDM process. Discharge pattern and gas film formation (size and stability) are two important events which were not affected by low frequency vibration.

Wutrich et al. applied low frequency vibration (5…30 Hz) to the tool. Results showed machining time for the vibration amplitude of 10 μm reduced about 50% which was a great achievement. Vibration amplitude higher than 10 μm did not effect on the MRR, significantly [14]. Razfar et al. studied the effect of vibration frequency (<500 Hz), amplitude (<27 μm), longitudinal waveform (Sinusoidal and Square) and tool shape (cylindrical or drilling tool) on the machining speed and hole depth. Results showed that the drilling tool achieved more efficiency in comparison to the cylindrical tool, but the application of vibration with square waveform to the cylindrical tool increased MRR about 40% while vibration did not effect on the performance of drilling tool, significantly [15].

Han et al. applied high frequency ultrasonic vibration (1.7 MHz) to the electrolyte in the drilling process. Ultrasonic vibration created acoustic pressure which resulted in more uniform gas film. Machining depth increased and holes with higher values of overcut were achieved. As another solution, the tool with the insulated wall and pulse voltage employed to improve the accuracy of holes. Finally, the hole diameter decreased from 426 to 328 μm and machining depth improved from 320 to 550 μm [16]. One of the main advantages of ultrasonic vibration is circulating the electrolyte into the hole, especially in the hydrodynamic regime (depth > 300 μm). In this research, ultrasonic vibration applied to all of electrolyte while a blind hole was machined. In other words, drilling of the blind hole was done on one side of the workpiece while ultrasonic vibration was applied to another side of the workpiece in the electrolyte. It seems that this manner for application of ultrasonic vibration cannot be effective, especially when the electrolyte circulated in the hole with depth more than 300 μm. On the other hand, applying ultrasonic vibration to all of electrolyte may lead to undesirable events, such decomposition of electrolyte on the anode surface, variation of conductivity and electrical properties and cavitation phenomenon which made ECDM process, uncontrollable.

Rusli et al. applied high frequency ultrasonic vibration (27–28 kHz) with an amplitude up to 3.5 μm on the glass workpiece in the drilling process. Results showed ultrasonic vibration with the amplitude lower than 2 μm created consecutive discharges which finally achieved greater MRR. On the other hand, ultrasonic vibration with the amplitude of 2 to 3.5 μm resulted in smaller MRR while the surface quality was improved. Three types of current waveform were observed. In the case of large amplitude, dense and wide current pulses had sporadic thermal energy related to consecutive discharges which were found for smaller amplitude, so MRR was reduced [17]. Same as previous research [16], ultrasonic vibration was applied to a large area of the workpiece which could led to undesirable events. For example, cavitation phenomenon occurred on all top surfaces of the workpiece, the hole bottom and wall. Cavitation on the top surface close to the hole may interrupted circulation of the electrolyte to the hole. On the other hand, cavitation on the bottom of hole created a layer of bubbles between the electrolyte and workpiece which acted as an insulator and reduced the thermal energy transferred to the workpiece.

Mentioned methods for application of ultrasonic vibration affected to a large area of configuration components and often increased cleaning procedure of the machining zone. On the other hand, during practical drilling process and in deep section of the hole, mentioned methods did not effect on the material removal elements in the machining area. To avoid undesirable and uncontrollable events, vibration should concentrate directly on the machining area in such a way that does not effect on the other components. Between machining components, tool tip is the best location for this purpose.

In this research, ultrasonic vibration is concentrated on the tool tip which directly and continuously effects on the machining zone and avoids global undesirable effects. Also, an analytical model is presented for both of the electro-chemical discharge machining (ECDM) and ultrasonic assisted electro-chemical discharge machining (UAECDM) to study the effect of ultrasonic vibration on the thickness of gas film. In the experimental section, a special configuration is designed to integrate the rotating tool and the greatest vibration amplitude on the tool tip. Numerical results are verified with experimental measurements of gas film in different condition. Machining depth is investigated to present capabilities of UAECDM to fabricate deeper hole compared to ECDM. On the

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