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Micro-hole fabrication on polymer by electrochemical discharge machining

Julfekar Arab[1,2] Shih-Chi Chen[1,2]

[1]*Department of Mechanical and Automation Engineering, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong*
[2]*Centre for Perceptual and Interactive Intelligence, Hong Kong Science Park, Shatin, N.T., Hong Kong*

arabjulfekar@gmail.com

Abstract

Micromachining of Polymer materials is vital for different micro/nano-systems such as micro-fluidics and micro-electronics. In recent times, the PMMA is demonstrated to be an upright candidate for the point-of-care microfluidic devices owing to its properties such as higher mechanical strength with relatively lower glass transition temperature, lower cost, and biocompatibility. Microfeatures such as holes and channels are important parts of a microfluidic device. Machining based on the electrochemical discharges (ECDM) has emerged as the cost-effective and simple method with relatively lower thermal damages with smooth sidewalls. In ECDM, the EC discharges generated at the micro-tool tip in the aqueous alkaline-KOH electrolyte and the following high heat energy due to the discharges eradicates the material from PMMA by heating, evaporation followed by thermal etching. In the current work, an attempt has been made to explore the micro-hole formation in PMMA polymer using ECDM for the first time. Identification of the electric power specifications (machining current-Im, machining voltage-Vm) and process parameters (KOH electrolyte-5M level-EL, machining time-Tm) has been done via experimentation and succeeding micro-hole geometric characteristics (size, depth heat affected zones) were analysed. The erosion of micro-tool after the ECDM have also been detected. The optimal range of parameters to get appropriate hole quality (optimal hole size: ~0.2±0.05 mm, and machining depth: ~0.103±0.03 mm) were found to be:-V:30 ± 0.5 V, Im:0.42±0.02 A, EL: 1.5 mm.

Keywords: PMMA, electro-chemical discharges, Polymers, micro-fluidics

1. Introduction

The need for micro structuring of electrically non-conductive materials utilising cost effective as well as efficient techniques rises from the increasing demand for micro/nano-scale structures and related devices in numerous fields, namely, microelectronics, healthcare, micro-fluidics etc. Electrically non-conductive materials, such as glass, ceramics, and polymers, are widely used in various fields, such as microelectronics, microfluidics, biomedical engineering, and optics [1,2]. These devices frequently need multifaceted, complicated and accurate features on electrically non-conductive materials such as glass and polymers with high accuracy. Micro fabrication of electrically non-conductive materials, such as glass, ceramics, and polymers, is a challenging task due to their high brittleness and low thermal conductivity.

Traditional methods, such as mechanical force-based milling or cutting, which includes high-speed rotating machining tool to eliminate material from the workpiece, are frequently futile as well as random and can consequence in less accurate as well as poor surface quality and micro-features dimensional accurateness [3]. Laser ablation and plasma-based etching are two well recognized methods. Laser ablation comprises using a high-energy laser beam to eradicate material. This technique gives high accuracy with ability to produce intricate geometries. Nevertheless, laser ablation has limits, such as inadequate material removal rates, exposure to thermal impairment, and high apparatus and maintenance related costs [4]. Plasma based etching can give very fine and miniaturized micro holes in electrically non-conductive materials. Yet, they need expensive equipment and complex tooling, cleanroom, lesser production rate and less cost-effective for minor productions [5,6].

In recent decade, electrochemical discharge machining (ECDM) has arose as a capable substitute for micro machining of polymer and related non-conductive materials [7]. Considering the competence of method, there is a rising interest in developing low-cost methods for ECDM-based micro machining. ECDM method proposes a cost-effective solution for micro machining of non-conductive materials, with potential applications in various fields [8]. Most of the works in the ECDM deals with glass-based micromachining using various types of the electrolytes, different shape/size tool electrodes, as well as machining approaches [9,10]. Very few researchers have discovered the capability of ECDM for other than glass material. Recently few researchers tried the fabrication of microchannels in PDMS and PMMA material [11,12]. Though, the experimental analysis is constrained preliminary inspections to microchannels only. Thus, there is a research gap for micro-fabricating this PMMA polymer material for micro-holes fabrications. This present article focuses on study of lower cost technique i.e. ECDM micro machining of PMMA polymer material. The range of values for process parameters (machining voltage and current) associated with the ECDM process are recognized and suitable values were confirmed for PMMA material for fabrication of blind micro holes.

2. Mechanism of ECDM process

Electro-chemical discharge machining is often understood as the mixture method of micro- machining that incorporates the EDM based process as well as the ECM based process [13]. Material eradicating mechanism includes thermal based melting at advanced localized temperature followed by the material evaporation. Furthermore, the chemical etching-based removal also takes place as the etching nature of the KOH electrolyte. The basic electrochemical cell and the setup of ECDM consists of the three main parts, i.e. tool, KOH electrolyte, and counter electrode.

The aqueous alkaline KOH solution is used as an electrolyte the conducts electric charge between the tool and counter electrode plate when a potential difference (V) is applied across them. The tool electrode is provided with negative polarity from power supply i.e. cathode and auxiliary electrode i.e. anode, as positive polarity is provided here from power supply. Due to application of the potential difference, the hydrogen gas bubbles creation starts which subsequently get collected around the tool surface making a gas film eventually. This gas film turns as an insulation barricade between the tool and the surrounding electrolyte. After the providing potential difference past a critical voltage, the gas film collapse resulting into the EC discharge generation. The discharge delivers the adequate heat energy to melt as well as evaporate as well as chemically etch the PMMA material reserved in the close neighbourhood of the tool [14].

3. Materials and methods

The experiments for the ECDM process carried out on an inhouse developed experimental set up as shown in the Fig.1. The main components electrochemical cell, tool fixture, and power supply unit. The electrochemical cell consists of the workpiece holder, counter electrode plate and electrolyte. The power supply with DC output used for all the experiments. The tool fixture is micro drill chuck attached vertical moving fixture. The details of parameters are shown in the following table 1.

Table 1 Processing parameters

Parameter	Value/remark
Workpiece and thickness	PMMA, 1-1.5 mm
Counter electrode	Stainless steel ring with thickness (dia.17 cm)
Tool immersion depth	1.5 mm
Tool workpiece gap	In contact position (~0 mm)
Power supply voltage	0-30 V DC
Power supply current	0-3 A
Electrolyte type	Potassium Hydroxide (KOH)
Electrolyte concentration	5 M aqueous
Tool electrode and tip diameter	Needle tool (0.09±0.02 mm)
Tool electrode material	Stainless steel

The tool -workpiece gap was kept as zero i.e. in contact position using a slip gauge of known thickness. The micro features obtained after the experimentations were characterized using the optical microscope (leica Inc.) to obtain the micro dimple size as well as the heat affected zone. The developed experimental set up as well as the tool electrodes optical image are illustrated in the following figure 1.

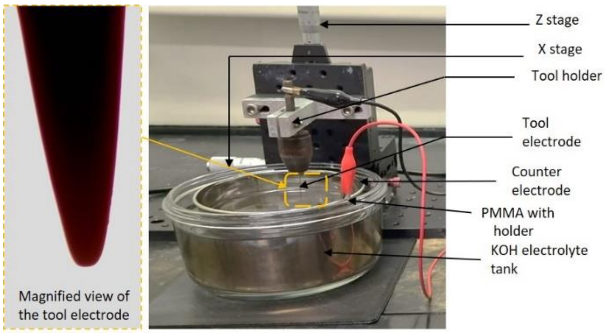

Figure 1. Experimental set up with all accessories and tool electrode

The circularity is measured as the ratio of the minimum to maximum micro-hole diameters whereas the HAZ was quantified by measuring the linear dimension of the thermally influenced areas at the peripheries of eopening end of the micro holes. The selected material for the analysis i.e. soda lime glass and PMMA have following important material properties as mentioned in the Table 2.

Table 2 Properties of the material and tool electrode

Properties/composition	PMMA	Stainless steel
Melting point (° C)	160	~1500
Electrical resistivity (Ω.m)	2×10^{15}	6.9×10^{-7}

4. Results and Discussions

In ECDM, the application of the sufficient voltage (>2-3 V) is allowed between the smaller tool electrode which is a cathode terminal and the larger counter ring electrode which anode terminal in an electrochemical cell, the electrolysis action of aqueous potassium hydroxide-KOH electrolyte happens. This results in generation of the gas bubbles of hydrogen (H_2) at cathode terminal and of oxygen(O_2) at anode terminal, respectively. At cathode H_2 gas bubble generation rate is very high as the current density is larger. Further increment in the voltage results into merger of gas bubble forming envelope of gas film around the tool electrode separating it from nearby electrolyte. This gas film layer is broken when voltage is elevated (> 24 V) and electrochemical discharges are produced. EC discharges generate heat energy which helps in material removal from the PMMA workpiece. The Critical point (~24 V) shown in the I-V curve is a point of highest value of the current is seen during the process and past which EC discharges are generated.

The identification of suitable machining voltage (Va) and corresponding mean discharge current (Id) in the EC discharge zone is important in order to get the precise micro-hole. Initially the machining voltage of 26 V i.e. VC+2 was used for formation of the micro-holes. Further, the machining voltage was varied with increase of 2 V. The Current-time (I-t) graphs are analysed first and are shown in the Fig. 2.

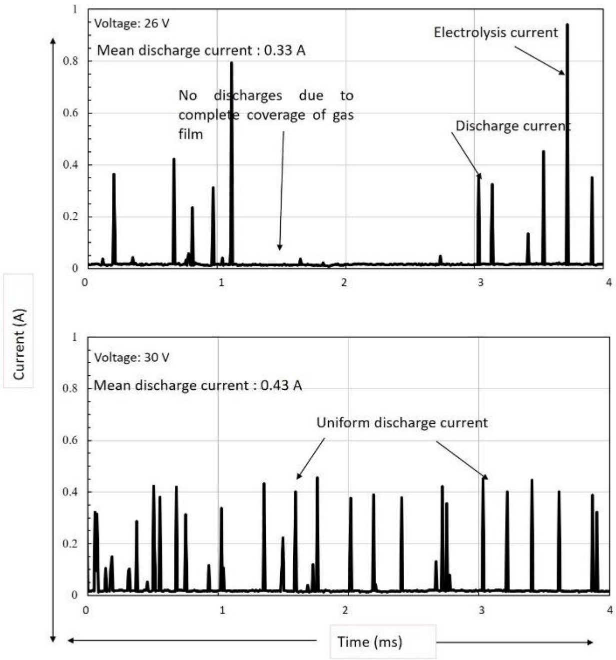

Figure 2. EC discharge behaviour different machining voltage

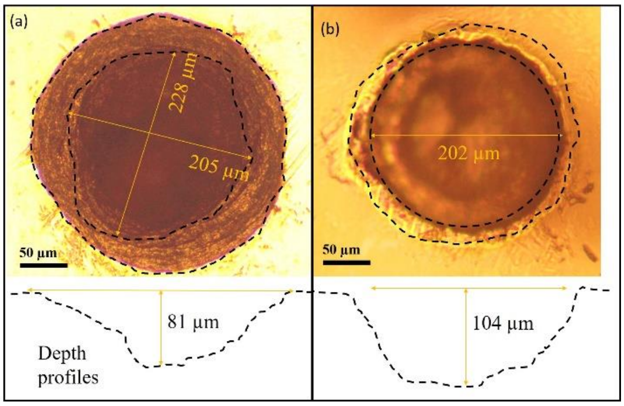

Figure 3. Machined micro-hole in the PMMA at different voltages (a) 26 V, (b) 30 V

Here, current values over the time step of 1 ms are recorded and it indicates the behaviour and trend of EC discharges as these parameters can influence as well as impact the micro-holes quality. EC discharges with higher uniformity and stability are essential to get circular, less thermally damaged micro holes with higher depths. I-t graphs were recorded and plotted by measuring the current values using multi-meter during the process. In case of 26 V machining voltage, the current spikes higher than Id of 0.33±0.02 A were measured as electrolysis current where sporadic gas film or incomplete merger of gas bubbles may be happening. When the Va was augmented to 30 V i.e. Vc+6 and the Id was recorded to be 0.42 ±0.02. Here, the current peaks are also steady and unvarying with no sporadic electrolysis current value. This clearly indicates appropriate collapse of H_2 gas film and generation of even uniform discharges.

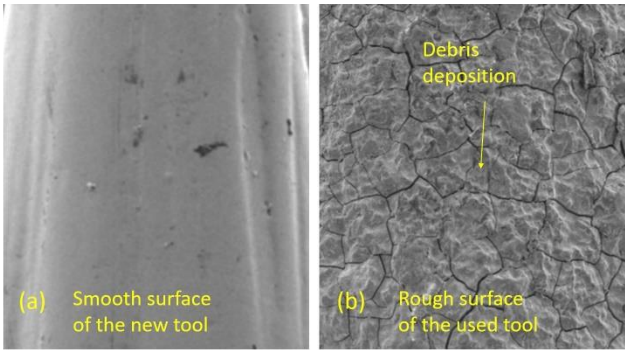

Figure 4. Tool electrode condition before and after machining

As can be seen from the Fig. 3(a), the micro hole at the voltage of 26 V which is Vc+2, has lesser circularity (0.83±0.05) and hole diameter with higher standard deviation (225 ±8 µm). The HAZ can be seen as non- uniform in nature having the higher value of 45 ±10 µm. The measured depth was 82 ±10 µm which is less due to the lesser depth of penetration due to non-uniform EC discharges. The micro hole with application of 30 V found to be having lesser HAZ (23 ±3 µm) and good circularity (0.96±0.01) as shown in the Fig. 3(b)

In case of 30 V highly consistent and uniform EC discharges occurred due to proper and complete collapse of gas film enveloped around tool electrode which resulted into appropriate circular holes with lesser standard deviation (size: 201±2 µm). Here, the measured depth is higher (102±1 µm) than the previous case due to higher penetration depth due to concentrated heat energy as a result of the uniform EC discharges with higher stability.

Next, to analyse effect of tool condition on the EC discharge behaviour and micro-hole features, new and used tools were recorded for the same applied voltage of 30 V. Fig. 4(a, b) shows the surface profiles for the fresh and used In case of used tool, where the tool was subjected to machining for a total time duration of 5 minutes, the EC discharges are observed to be unstable with intermittent electrolysis current peaks indicating intermittent gas films formation and its due to the fact that the used tool electrode surface was observed to be eroded and machining debris deposition which led to non-uniformity and irregularity in the machined depth. The possible remedies for reduction in tool wear will be the use of sidewall coating of non-conductive nature which may result in the reduction of stray EC discharges from the sidewall. Moreover, providing the tool vibration mat possibly reduces the tool erosion.

4. Conclusions

The ECDM process capability to machine the micro-holes in PMMA is demonstrated successfully. The major parameter i.e. machining voltage and its effect on EC discharges and subsequent micro hole quality has been studied The machining voltage desirable for the suitable machining quality with unvarying EC discharges should be 4-6 V higher than the critical voltage. The optimal hole quality with higher circularity, higher depth as well as lower HAZ obtained when suitably high voltage of 30 V is applied. The lesser values of voltage (26 V) which indicates the region of instability leads to uneven as well as non-uniform EC discharges, which resulted into high deviations into hole size, HAZ and lesser depths. The EC discharge quality also degrades in case of the used tool with poor surface quality.

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