Geometrical improvement in machined micro-hole using adaptive tool feed system in electrochemical based discharge machining

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Abstract. Electrochemical based discharge machining (ECDM) removes the material by utilizing the thermal heating of the sparks followed by the chemical action. The tool feed method in ECDM controls the geometrical accuracies since gravity assisted and constant tool feed results in tool contacts that further deteriorates the micro-hole geometry. Moreover, high number of thermal cracks are produced with these tool feed methods. The present study investigates the adaptive tool feed system that withdraws the tool in upward direction when its contact with the work material is observed. Adaptive tool feed results in minimum tool contact and enhances the geometrical accuracies of the micro-holes. Hole circularity error (HCE) is taken as the response parameters for investigating the geometrical accuracies. The microscopy images reported a significant improvement in the geometry of the micro-holes machined with adaptive tool feed when compared to other tool feed methods. An improvement of 43.7\% in HCE is acquired with the application of adaptive tool feed at 40 V. Moreover, the effect of input parameters on geometrical characteristics in terms of HCE is also discussed. The present study successfully reports the geometrical improvement of micro-holes in ECDM.

Keywords: Adaptive tool feed, tool contacts, Micro-holes, ECDM.

1. Introduction

The demand of geometrical accuracies during the fabrication of micro-features on advanced materials is increasing over the past decades ease because of increased applications in Micro-electro-mechanical system (MEMS). It further lays down the platform for investigating the new methods of machining these materials with improved geometries. ECDM is known to be a blend of popularly known methods i.e., electric discharge machining (EDM) and electrochemical machining (ECM). The principle schematic diagram of the process is shown in Figure 1., consists of two electrodes dipped in aqueous electrolyte solution along with the work material. The tool electrode is built as cathode while auxiliary electrode is built as anode, NaOH and KOH are the generally preferred electrolytes for machining with ECDM. With the
supply of applied voltage, there is a development of small hydrogen and oxygen bubbles at the tool electrode and auxiliary electrode respectively. The hydrogen bubbles start joining each other in order to form a big size bubble with the increase in voltage supply. These big size bubbles form an isolating gas film at the tool electrode surrounding; thereby constricting the flow of current within the circuit. Thereafter, the sparks are produced due to the electric breakdown of the film (consisting immense electric field). The spark striking is the reason that material gets removed from the work material followed by the chemical dissolution. The work material needs to be placed under the tool tip at a very small distance known as a machining gap. The process is first reported by Kurafuji and Suda [1] during glass drilling with the electric discharge. The spark mechanism in ECDM was briefly described by Basak [2,3] during micro-machining with ECDM process and highlighted those critical values of both applied voltage and current is required to initiate the sparks. Jain et al. [4] successfully described the thermal heating phenomena alongside chemical action during machining micro-holes. Wuthrich et al. [5-6] made various contributions in the field of ECDM discussing critical parameters such as tool feed, gas film etc. Rajput et al. [7] described the use of gravity tool feed for machining micro-holes on glass materials and emphasized that higher number of thermal cracks were formed with gravity tool feed method. It produces poor circularity of the micro-holes. Ziki et al. [8] demonstrated the application of constant tool feed method and elaborated that it resulted into the tool stick and jump phenomena with the material. It produces poor geometrical characteristics in terms of hole circularity error (HCE). It is observed that tool feed higher than the mean material removal causes unnecessary tool contacts and deteriorates the micro-holes characteristics. Rajput et al. [9] optimizes the ECDM parameters with tool contacts (TC) as one of the response parameters and concluded that the combined increase of applied voltage and concentration alongside low level of tool feed rate results in a smaller number of tool contacts. However, many numerical and experimental studies have been reported covering different aspects of the process and exploring different areas to improve its performance [10-11].

1.1. Problem formulation

Despite having various experimental studies, very rare studies concerning the tool contacts with the material is performed. Additionally, controlling tool feed according to the material removal is rarely described in the literature studies. Improving geometrical accuracies or HCE of the micro-holes is still a challenging task. This present study investigates the application of adaptive tool feed to improve the
geometrical characteristics of the micro-holes. It monitors the tool feed with respect to the material removal rate and controls tool feed accordingly. The prevention of unnecessary tool contacts is provided to enhance the geometrical accuracies and HCE of the micro-holes. Additionally, the effect of input parameters on HCE is also observed under different machining conditions.

2. Methodology and Measurement

The experiments are conducted on a developed experimental setup using one factor at a time (OFAT) approach. The soda lime glass is selected as a work material for performing the micro-drilling operations. The cylindrical shaped stainless-steel tool of 1 mm diameter is considered as a tool electrode. Table 1 gives the machining conditions utilized for studying the geometrical characteristics of the micro-holes. The machined holes are assessed using a stereo microscope (model: Stemi-305 Trino, make: Carl Zeiss installed with Zen blue software) from the hole entrance side in order to study the geometrical characteristics. Applied voltage (V), tool feed rate (mm/min) and electrolyte concentration (wt.%) are chosen as an input parameter while geometrical accuracies in terms of HCE is chosen as a response characteristic.

Table 1. Machining conditions used in the present study.

| Parameter     | Range/Value | Parameter     | Range/Value |
|---------------|-------------|---------------|-------------|
| Tool electrode| Stainless steel | Applied Voltage | 35 -50 V   |
| Auxiliary electrode | Graphite | Electrolyte concentration | 15 wt.%-30 wt.% |
| Electrolyte   | NaOH        | Tool feed rate | 3-5 mm/min  |
| Machining time| 2 minutes   | Inter-electrode gap | 40 mm     |

2.1. Experimental setup

The adaptive tool feed experimental setup is fabricated in the laboratory and attached to the vertical milling machine as shown in Figure 2. It consists of force sensor or load cell that senses the presence of tool force when its contact with the material takes place. It works on the principle of closed loop system and controls the tool feed accordingly i.e., tool monitoring system. The load cell develops a signal once its contact is detected and send it to the controller. The controller further removes the tool contact by moving it in opposite direction. As a result, the tool contacts are prevented during micro-drilling process.

![Figure 2. Developed experimental setup of adaptive tool feed system [9].](image)

2.2. Hole circularity error (HCE)

It is described as the out of roundness error and indicates the hole geometrical accuracies. It is measured as described in Figure 3.
3. Results and Discussions

The microscopy images of the micro-holes are analyzed for comparing the geometrical accuracies with and without adaptive tool feed. Figure 4 shows the comparison of micro-holes machined at 35 V and 15 wt.% using 3 mm/min tool feed rate. It is seen that the micro-holes machined with adaptive tool feed system exhibits better geometrical accuracies in terms of roundness (Fig. 4(b & d)) when compared to geometrical accuracies obtained without adaptive tool feed system (Fig. 4(a)). Adaptive tool feed results in lesser number of tool contact that prevents the production of unnecessary thermal cracks. Moreover, adaptive tool feed helps in attaining a constant machining gap that enables the availability of the electrolytes under the tool for a constant and consistent formation of the gas film. As a result, more channelized sparking takes place and better geometrical accuracies are obtained. On the contrary, a permanent contact is seen in gravity tool feed that causes more thermal cracks at the hole boundary. Also, no gas film is observed under the tool tip due to its contact and hence, poor geometrical characteristics are observed (Fig.4(c)). Table 2 presents the experimental results of HCE obtained during the study. Figure 5 shows the plot of circularity error with and without application of adaptive tool feed at different applied voltages when machined with 15 wt.% NaOH concentration and 3 mm/min tool feed rate. It is depicted that the circularity error improves with the utilization of adaptive tool feed as discussed. An improvement of 43.7 % in circularity error is obtained with the application of adaptive tool feed at 40 V (Fig.5).

Figure 4. Comparison of micro-holes drilled with different tool feed method (a) Without adaptive tool feed (b) adaptive tool feed (c) Gravity tool feed (d) adaptive tool feed.
Table 2. Experimental data obtained in the present study.

| A (V) | Without Adaptive Tool feed | Adaptive Tool feed | B (wt.%) | Without Adaptive Tool feed | Adaptive Tool feed | C (mm/min) | Without Adaptive Tool feed | Adaptive Tool feed |
|-------|-----------------------------|--------------------|----------|-----------------------------|--------------------|------------|-----------------------------|--------------------|
| 35    | 0.0331                      | 0.029              | 15       | 0.0533                      | 0.019              | 3          | 0.0533                      | 0.019              |
| 40    | 0.0427                      | 0.024              | 20       | 0.068                       | 0.015              | 4          | 0.068                       | 0.025              |
| 45    | 0.0533                      | 0.019              | 25       | 0.071                       | 0.011              | 5          | 0.078                       | 0.034              |
| 50    | 0.0786                      | 0.028              | 30       | 0.083                       | 0.018              |            |                             |                    |
| 55    | 0.0813                      | 0.037              | 35       | 0.089                       | 0.021              |            |                             |                    |
| 60    | 0.0832                      | 0.048              |          |                             |                    |            |                             |                    |

A: Applied Voltage, B: Electrolyte concentration, C: Tool feed rate

Figure 5. Comparison of HCE at different applied voltage with and without the application of adaptive tool feed system.

3.1. Effect of applied voltage on HCE

It is known fact that the level increase in applied voltage causes the increase in formation rate of small bubbles inside the electrolytes also increases that further give rise to the increase in sparking action [12]. Thus, an increase in material removal occurs that further leads to the prevention of the tool contacts. As a result, it is expected to obtain better geometrical characteristics or improved HCE since less tool contacts are obtained. But there is also a high possibility of side sparking from the tool sides that may causes a deterioration of the geometrical accuracies. Hence, poor circularity is developed. Figure 5 shows the trend of HCE with respect to applied voltage with and without the application of adaptive tool feed system. It is seen that without adaptive tool feed system, there is an increase in HCE with the increase in applied voltage due to high side sparking and high tool contacts. On the contrary, HCE improves with the level increase in applied voltage up to 45 V due to decrease tool contacts but an increase in HCE is observed with the further increase in applied voltage above 45 V at a constant tool feed rate of 3 mm/min. Gravity tool feed extensively produces a high HCE due to the tool permanent contact with the work material (Fig.4(c)).
3.2. Effect of electrolyte concentration on HCE

The effect of electrolyte concentration on HCE is observed similar as seen in case of applied voltage. HCE decreases with the increase in electrolyte concentration up to 25 wt.\% and then an increase in HCE beyond 25 wt.\% is observed at 45 V. Increase in electrolyte concentration leads to the enhanced frequency of the sparks that further removes the material faster. It reduces the contact of the tool with the work material. A further increase in concentration may leads to side sparking from the tool sides; as a result, poor circularity is observed [13]. Figure 6 shows the trend of HCE with respect to electrolyte concentration with and without adaptive tool feed system.

![Figure 6](image)

**Figure 6.** Comparison of HCE at different electrolyte concentration with and without the application of adaptive tool feed system.

3.3. Effect of tool feed rate on HCE

Tool feed significantly controls the geometrical accuracies of the micro-holes since too high tool feed rate results in high tool contacts. As a result, may deteriorates the hole circularity. Any level increase in applied voltage and electrolyte concentration produces more sparks over the work material. Thus, a combination of higher level of these two alongside low levels of tool feed rate results in better hole circularity. Figure 7 shows the trend of HCE with respect to tool feed rate with and without adaptive tool feed system.

![Figure 7](image)

**Figure 7.** Comparison of HCE at different tool feed rate with and without the application of adaptive tool feed system.
4. Conclusions

The present article investigates the use of adaptive tool feed system for improving the geometrical accuracies of the micro-holes in terms of hole circularity error (HCE). The influence of input parameters on HCE is also discussed. The conclusions are given below:

- The adaptive tool feed-based system is a successful method in improving the geometrical accuracies of the micro-holes.
- Adaptive tool feed minimizes the tool contacts with the material and improves the formation of gas film under the tool tip.
- The combined effect of tool feed rate, electrolyte concentration and applied voltage control the contact of the tool with the material. Higher level of electrolyte concentration and applied voltage alongside low tool feed rate are preferable for controlling the geometrical accuracies. It produces better hole circularity during micro-drilling operation.
- An improvement of 43.7% in circularity error is observed with the application of adaptive tool feed system in ECDM at 40 V.
- An increase in the level of applied voltage and electrolyte concentration results in better circularity up to some extent, thereafter a deterioration in circularity error is seen due to increase in side sparking.

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