

Effect of Outflow Mode on Machined Micro-dimple in the Through-mask Electrochemical Micromachining with Filled Inter-electrode Gap

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Abstract. To analyse the effect of outflow modes during making micro-dimples using the modified through-mask electrochemical machining with filled inter-electrode gap, some investigations were carried out numerically and experimentally. The studies showed that, the reflux discharging mode (RDM), which allows most of the electrolyte and electrolytic products to flow out through the holes arranged inside the cathode, can produce fairly more homogeneous flow field and smoother mass transfer during machining, compared with the conventional mode in which the electrolyte and electrolytic products can be discharged only from the inter-electrode gap. Micro-dimples generated on the basis of RDM show a flat bottom feature without island defect and smooth surfaces as well as good dimension uniformity.

Introduction

Surface texture such as micro-dimple arrays can enable some products to decrease friction, increase heat transfer and improve flow condition [1,2]. Therefore, it is one of main tasks in surface engineering to optimally design and manufacture the desirable surface textures. At present, various techniques are used to manufacture surface textures. They include vibration machining, laser-beam machining, electrical discharge machining, abrasive jet machining, electrochemical machining (ECM) and so on. Among them, ECM is a non-traditional machining technique based on the principle that anodic dissolution occurs electrochemically at the metallic workpiece with electrolyte flowing, and it has a number of advantages over other techniques. ECM technique can be applied nearly all kinds of metallic materials, and gives no additional residual stress and recast layer to the machined surfaces during machining which often appear in mechanical and thermal processes. Generally speaking, ECM is classified into two groups— through mask ECM (TM-ECM) and maskless ECM [3]. Comparatively, TM-ECM process is more widely used for machining various metallic surface textures because it can be carried out in a large production run. However, the conventional TM-ECM process is time consuming and tedious because it involves a series of steps with a number of influencing parameters to prepare the through-mask by means of photolithography process, and thus is very hard to be applied to the non-planar surfaces due to the limitations of photolithography process. Additionally, the through-mask of TM-ECM process has been prepared repeatedly for each workpiece and thus is costly. Consequently, some efforts have been made to improve the TM-ECM process. In 2005, in order to improve the efficiency of traditional TM-ECM and to avoid preparing through-mask repeatedly, a nonconventional ECM technique that the patterned mask was adhered to the cathode instead of the anode was presented by Roy et al [4], but in principle the machining accuracy and selectivity could not be expected to be high.

To eliminate the use of the adhesive mask and thus to simplify the TM-ECM process, Zhu et al [5,6,7,8] innovatively utilized the active through-mask that can be removed from the anode and reused repeatedly, and studied experimentally and numerically its effects on the dissolution behaviors and machining accuracy. However, fixing such removable mask could be a challenging task. A fixing method by using micro-column arrays to press the active mask was presented in the Refs. [9,10]. This dot-pressing fixing manner could hardly be used to the cases where the workpiece is non-planar and the pitch of patterned structures in the through-mask is considerably small, for example, the pitch is

less than 500 μ m. Consequently, a modified means for fixing the active mask was developed by our group [11,12]. In the modified fixing manner, the through-mask is pressed by a layer of flexible porous against the workpiece anode, and the flexible porous material, which can allow liquid to flow through, is filled into the inter-electrode gap and also is acted as a medium to transmit the force from the cathode to the through-mask. It has showed that the TM-ECM with flexible filler can significantly accommodate the fixation and pressure of the through-mask on the non-planar workpiece, regardless of the pitch of through-mask. It is, of course, predictable that the filled flexible material within the inter-electrode gap can affect the mass transfer characteristics and possible electric field distribution. Therefore, the discharging of electrolyte and by-products from the inter-gap should be an important consideration for this modified TM-ECM. In the following sections, optimization of discharging mode is investigated emphatically.

TM-ECM with Its Inter-Electrode Gap Filled with Flexible Porous Material and Electrolyte Output Mode

For this newly developed TM-ECM, the unique feature is the addition of insulative flexible porous material filled the inter-electrode gap. This kind of material accommodate the fixturing of removable through-mask, but at the same time it may adversely influence mass transfer effect and electric field distribution, thus making the process less quality. It is known that the excessive electrolyte and by-products have to be discharged only from inter-electrode gap in the typical TM-ECM processes, called side-opening discharging mode (SODM) here, as shown in Fig. 1a. This discharging mode could be very difficult to produce a uniform mass transfer filed in the case of large-area workpiece of ECM and thus is hardly applicable to the newly developed TM-ECM with fillings in the inter-electrode gap introduced in this paper. Therefore, it is very necessary to exploit a more effective method to make the mass transfer much better when utilizing this modified process. In this paper, as shown in Fig. 1b, a specially designed tool-cathode, also used as an electrolyte outflowing structure, was developed to allow most of the electrolyte and by-products to flow out directly from the outlet passages which are arranged inside the tool-cathode. Its working principle is shown in Fig. 1c. The electrolyte is pumped to the inter-electrode gap through the inlet passages which are also arranged inside the tool-cathode, and then it fills into the flexible porous material and further reaches the exposed area of the workpiece via through-mask, where the electrochemical dissolutions occur. Most of electrolytic products during electrochemical dissolution flow out directly through the outlet passages, with the rest being discharged through the inter-electrode gap. Although the inlet passages and outlet passages are all arranged in the same body, they are isolated and each functions itself as an independent passage. This discharging mode is termed as reflux discharging mode (RDM) here. In the following, simulations of mass transfer field distribution from the two modes will be carried out.

Flow Field Simulation and Analysis

To accommodate the simulations, some assumptions are made as follows. (1) the structures and thickness of the flexible porous material are homogeneous and the resistance coefficient of material layer is the same at every unit area; (2) there is no energy loss during electrolyte flow and the electrolyte temperature is constant; (3) the electrolyte contains only liquid-phase substances; (4) no electrochemical dissolutions take place; (5) there is no electrolyte at the interfaces between the flexible porous material and the through-mask, and between the mask and workpiece; (6) the pressure in the exit is a standard atmospheric pressure.

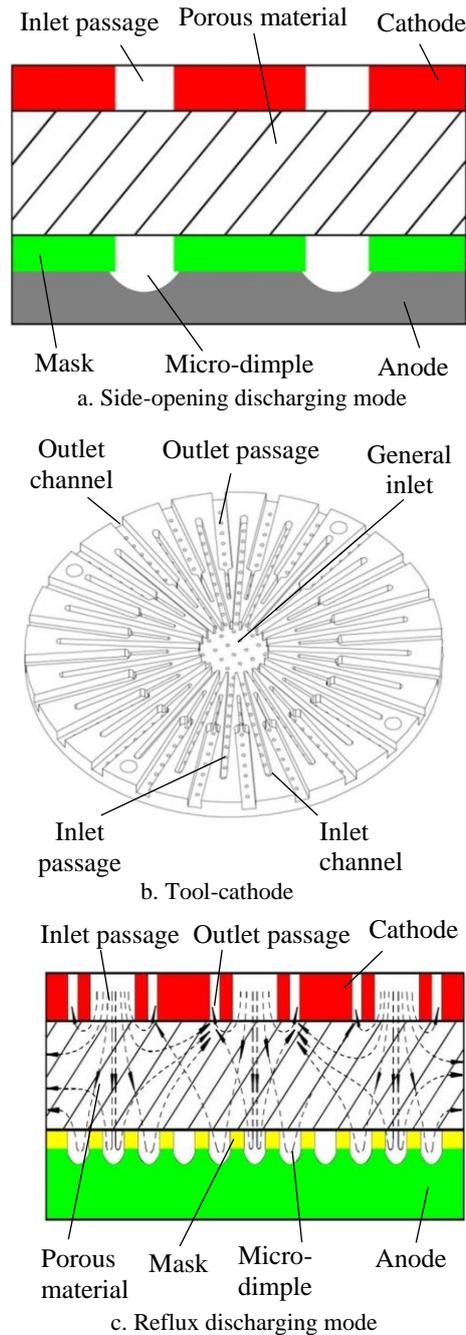
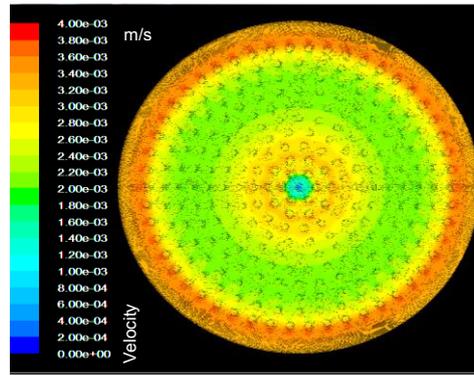
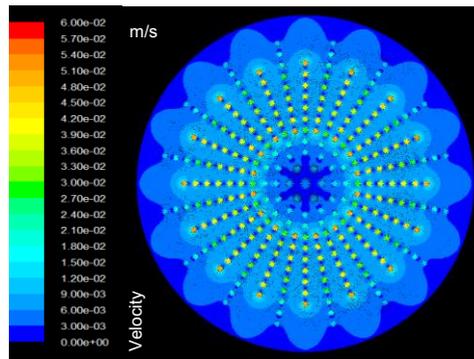


Fig. 1. Through-mask electrochemical machining and its discharging modes

The simulations are performed based on commercially professional software FLUENT 6.3 using the standard $k-\epsilon$ turbulence model. The main parameters and conditions for the simulations are shown in Table 1. Fig. 2a illustrates the flow field distribution within the inter-electrode gap. As a whole, the distribution of flow field is relatively homogeneous and the flow velocities are the same order of magnitude about $1 \times 10^{-2} \sim 2 \times 10^{-2}$ m/s in the reflux discharging mode. In contrast, as shown in Fig.2b, the flow field in the inter-electrode gap based on the conventional SODM (no outlet passages within the tool-cathode) is much more inhomogeneous, and the flow velocities are also fairly smaller ranging from about 6×10^{-4} to 4×10^{-3} m/s. In conventional SODM, only the inlet passages (diameter 1 mm, pitch 2 mm) are provided. Other parameters are the same to the former. The numerical simulation results reveal that a relatively uniform flow field and desirable mass transfer rate can be obtained in the RDM. Experimental investigations will be done in next section.



a. Reflux discharging mode



b. Side-opening discharging mode

Fig. 2. Flow field simulation under two modes.

Table 1. Main parameters and values used for the analysis of flow field

| Items | Values or variables |
|--|---------------------------|
| Electrolyte | 20 wt.% NaNO ₃ |
| Temperature/T | 25 [°C] |
| Input pressure/P | 1 [MPa] |
| Flexible porous material (polypropylene) thickness/h | 0.2 [mm] |
| Porosity of flexible porous material | 20% |
| Size of general inlet/D1 | Φ10 [mm] |
| Cathode diameter | Φ40 [mm] |
| Cathode thickness | 3 [mm] |
| Size of outlet passage/D2 | Φ 0.5 [mm] |
| Size of inlet passage /D3 | Φ 0.5 [mm] |
| Diameter of hole in the general inlet/D4 | Φ 0.8 [mm] |
| Diameter of workpiece anode | Φ40 [mm] |
| Outlet channel width/ L1 | 1 [mm] |
| Outlet channel width/ L2 | 2 [mm] |
| Inlet channel width/L3 | 1 [mm] |
| Angle between two neighboring inlet channel/β | 22.5 ° |
| Angle between inlet and outlet channel/α | 11.25 ° |
| Channel depth | 1.5 [mm] |
| Pitch of the outlet passage /d1 | 3 [mm] |
| Pitch of the inlet passage /d2 | 2 [mm] |
| Force on flexible porous material | 10 [N] |

Experiments

In the experiments, the tool-cathode is made of brass and its geometrical parameters are the same to those used in the numerical simulation. The workpiece is stainless steel sheet (SUS304) and its diameter is 40 mm. A pulsed power supply is used. The applied voltage is 12V-16 V (for RDM) and 21V-24 V (for SODM). The through-mask thickness is 0.1 mm and the diameter of patterned holes is 0.5 mm, having the aspect ratio of 0.2. Machining time is 3 minutes for RDM and 1 minute for SODM, respectively. Other main experimental parameters are shown in Table 2.

Table 2. Machining parameters for the experiments

| Items | Number or condition |
|--|------------------------------------|
| Mean diameter of porous material's holes | 100 [μm] |
| Porous material | Polypropylene microporous membrane |
| Number of holes in the mask | 13 |
| Voltage | 12,14,16,21,24 [V] |
| Input flux | 4 [L/min] |

The feature and contour of micro-dimples are characterized and observed by the digital camera, hyper-focal distance microscope system (VHX-2000, KEYENCE, Japan) and SEM (SH4000M, HIROX, Japan). In order to accommodate to analyze the size distribution (depth and diameter) of micro-dimples machined, 13 representative micro-dimples are selected.

Results and Discussion

Profiles of Micro-Dimple Machined In Two Modes

As shown in Fig. 3, for SODM, the bottom of micro-dimples machined is generally out of flatness and somewhat coarse and island defect can be observed frequently in some micro-dimples. In contrast, for RDM, the bottom of micro-dimples is in a basin shape with relatively smooth surface, and few island defects can be seen. These findings show experimentally that better geometric accuracy of micro-dimples can be obtained during the TM-ECM with the RDM probably due majorly to the relatively quick flow rate and fairly uniform mass transfer which have been verified numerically.

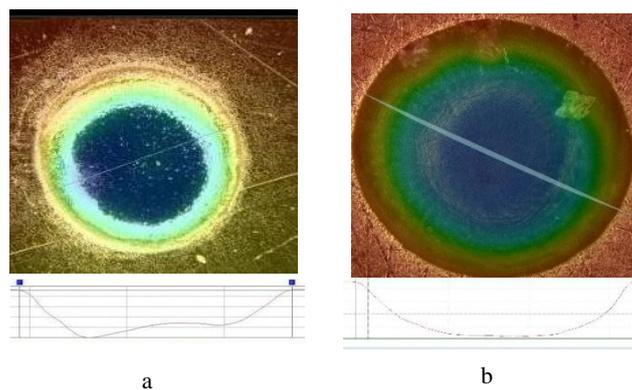


Fig. 3. Microscopic image of micro-dimple on SODM with 24V (a) and RDM with 16V (b)

Geometric Dimensions

Fig. 4 shows the dimension (depth and diameter) distribution of micro-dimples generated under different process parameters on the basis of SODM and RDM. It was found that the depth and diameter of micro-dimples generated from SODM are generally bigger than those from RDM, and their variation ranges are also wider.

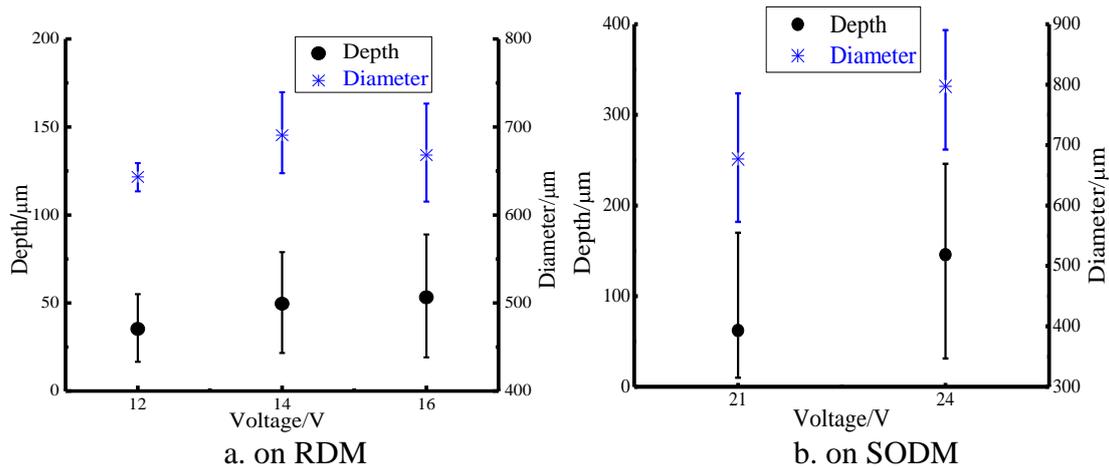


Fig. 4. Dimension of depth and diameter of micro-dimples on the basis of two modes

In this paper, dimension variance is introduced to evaluate the dimension distribution uniformity of micro-dimples machined. As shown in Fig. 5, the statistic depth variance and diameter variance calculated from SODM are beyond 2000 and 3000, respectively, while they are no more than 555.2 and 1155.5 respectively from RDM with the applied voltages. These findings show that the dimension uniformity of micro-dimples produced by using RDM is considerably higher than that by using SODM, which also reflects variation in the uniformity and rate of mass transfer during machining under two modes. At the same time, the findings indicate that the simulations of mass transfer agree well with the experimental results.

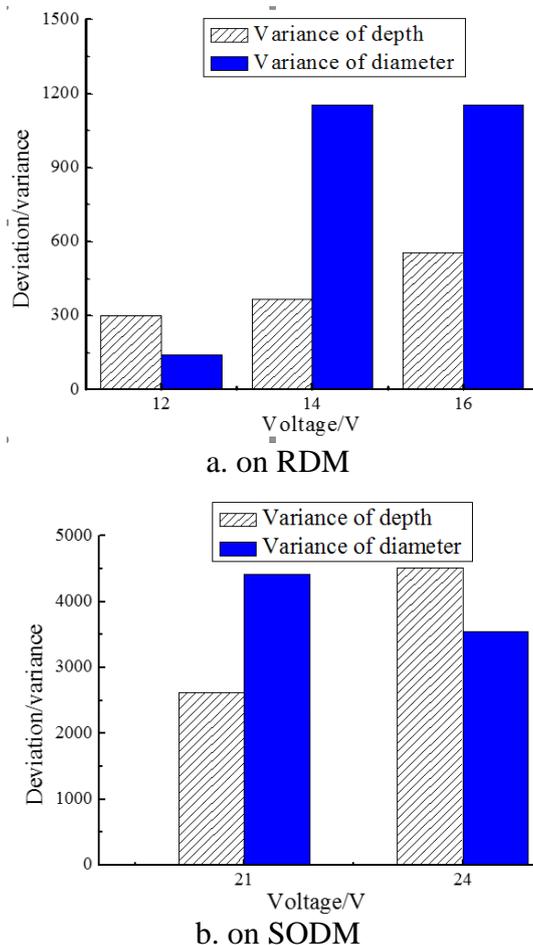


Fig. 5. Deviation of depth and diameter of micro-dimples on the basis of two modes

Conclusions

A new electrolyte discharging mode (RDM) has been exploited to make newly developed TH-ECM with filled flexible porous material in the inter-electrode more effective. Flow field distribution was numerically simulated, and some investigations were performed experimentally to analyse the effect of RDM on the machined micro-dimples. Micro-dimples machined on the basis of RDM have smoother surface, much better geometric accuracy, less island defects at the bottom, and less dimension variance compared with the conventional side-opening discharging mode, due mainly to the achievement of more uniform mass transfer field and more unhindered discharging environment.

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