Proceedings of the 8th International Conference on MicroManufacturing
University of Victoria, Victoria, BC, Canada, March 25-28, 2013

Field Induced Jet Micro-EDM

ICOMM 2013 No.

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ABSTRACT

Electrical discharge machining (EDM) is of the potential of micro/nano meter scale machining capability. However, electrode wear in micro-EDM significantly deteriorates the machining accuracy, thus, it needs to be compensated in process. To solve this problem, a novel micromachining method, namely field induced jet micro-EDM, is proposed in this paper, in which the electrical field induced jet is used as the micro tool electrode. A series of experiments were carried out to investigate the feasibility of proposed method. Due to the electrolyte can be supplied automatically by the capillary effect and the electrostatic field, it is not necessary to use pump or valves. The problem of electrode wear does not exist at all in the machining process because of the field induced jet will be generated periodically. It is also found that the workpiece material can be effectively removed with a crater size of about 2μm in diameter. The preliminary experimental results verified that the field induced jet micro-EDM is an effective micromachining method.

Key Words: micro-EDM, field induced jet, micro tool electrode

INTRODUCTION

The miniaturization of products is one of the developing trends of modern production[1]. Micro- and Nano-machining technology is the key to achieve product miniaturization[2]. One bottleneck in micro- and nano-machining field is the lack of effective methods to make features in the range of 100nm-1μm with low cost. At this level of resolution, it is not easy to combine conventional UV photolithography and wet or dry etching techniques like Reactive Ion Etching (RIE) or deep RIE (DRIE). Of course it is possible to make use of e-beam lithography, LIGA and Focused Ion Beam (FIB). These technologies are extremely expensive and time consuming and must be operated by highly skill personnel[3]. Thus, extensive application of these micro/nano fabrication technologies into cost-effective domain is constrained.

Electrical discharge machining (EDM), as a noncontact machining method, its machining performance has nothing to do with the mechanical properties of materials to be processed such as hardness, toughness, strength and so on. By controlling the discharge energy per pulse, extremely small discharge crater can be obtained, thus, EDM is of the potential of micro and even nano meter scale machining capability[4]. Currently, the possibility, craft and machining mechanism of nano-EDM are being widely explored and researched. Usually the scanning probe microscope is used as experimental platform and the nanometer scale tip of the probe is used as the tool electrode. Though the mechanism of material removal has not been well explained yet, it is believed that in nano-EDM there is an electric field assisted trapping and localized assembly of liquid medium molecules between the electrode and the metal substrate[5].

The tool electrode wear inevitably exists in EDM process, especially in micro/nano-EDM it will significantly deteriorates the machining accuracy[6]. Thus, it needs to be compensated online. On the other hand, the nanometer scale tip of probe used in nano-EDM is usually eroded easily and quickly. Since it is difficult to measure the actual tool electrode wear online, its compensation has become one of the major issues which restrained the applications of micro/nano EDM[7].

This paper proposes a novel micro machining method, namely field induced jet micro-EDM, in which the electrical field induced jet is used as the micro tool electrode. A series of experiments were carried out to investigate the feasibility of the newly developed method.

PRINCIPLE OF FIELD INDUCED JET MICRO-EDM

A. EXPERIMENTAL SETUP

Fig. 1 shows the experimental setup of field induced jet micro-EDM. The workpiece is mounted on a work table. A nozzle and syringe set, which served as the reservoir of electrolyte, are installed with a fixture fixed on the motion platform. The gap between the nozzle and the workpiece can be adjusted by the motion platform. The workpiece and nozzle are connected to a high-voltage DC power supply. The polarity of the nozzle is negative and the workpiece is positive respectively. The intensity of electrostatic field can be varied by regulating the output of HV DC power supply and adjusting the gap between the nozzle and the workpiece. The insulated base and the work table are made of Teflon (PTFE), which is of good insulativity for high voltage and chemical stability. Sodium nitrate aqueous of Wt 20% is used as the electrolyte in this study. The liquid jet is induced by electrostatic field and the electrolyte can be fed from syringe to the outlet of nozzle automatically by the capillary effect. Thus, no extra liquid supplying devices like pump or valves are needed in the experimental setup.

B. PRINCIPLE OF MACHINING

Fig. 2 shows the concept of field induced jet micro-EDM. An intense electrostatic field is formed while high voltage is applied between metal nozzle and workpiece as shown in Fig. 2(a). Electrolytic aqueous solution inside the metal nozzle will be extracted out and form an extruded liquid cone (also called Taylor cone[8]) at the tip of the nozzle with the effects of both surface tension and electrostatic force. Fig. 2(b) depicts the gap phenomena between the workpiece and the nozzle. The tip of the liquid cone emits a very fine jet hereinafter refers to as field induced jet, while the electrical potential is intense enough. This phenomenon is dominated by both the concentration of electrical charge at the tip of liquid cone and the surface tension of the electrolyte[9]. When the jet approaches the surface of the workpiece, the discharge ignites by the high voltage, breaking down the air in the small gap between the front end of the jet stream and the surface of the workpiece thereby a plasma column is generated. The material of the workpiece surface heated by the plasma column melts and evaporates in a very short period of time. In the end of the discharge, the plasma column collapses, inducing an explosive removal of molten and evaporated workpiece material at the discharge spot. As a result, a small crater is generated on the workpiece surface. At the same time, the jet stream is crumbled by the discharge as shown in Fig. 2(c). Then the liquid cone shrinks by the effect of the surface tension.

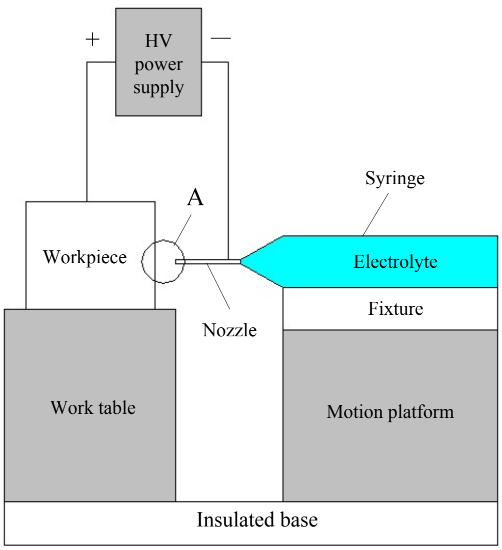


Fig. 1: Experimental setup of the field induced jet micro-EDM

FIELD INDUCED JET MICRO DISCHARGE

A. OBSERVATION SYSTEM

The dynamic jet stream generated at the tip of liquid cone is very fine and the duration of each discharge is extremely short. Therefore, it is difficult to precisely observe the generation process of the jet stream and the consequent discharge phenomenon. High-speed photography technology is a directive and effective method for capturing and recording the transient and high-speed motion processes. Real-time target capture, quick image recording and instant image playback are prominent advantages of this technology[10]. It is used to observe the field induced jet and consequent micro discharge process. Fig. 3 shows the setup of the observation system with a high-speed camera by which the generation process of the field induced jet micro discharge is recorded.

B. PROCESS OF FIELD INDUCED JET MICRO DISCHARGE

A number of shots of video images have been taken by the high-speed camera during the experiments. Fig. 4 shows the evolution of the field induced jet micro discharge in consecutive images from a video in which each image is recorded in every 25 µs. The size of each image is 160×40 pixels. The nozzle used in the experiments is 200µm in inner diameter. The upmost image shows the front end of the nozzle when there is no electrostatic field applied between the nozzle and the workpiece. The time zero is marked at the frame in which the jet started to be generated on the tip of the liquid cone and the electrical potential is applied between the workpiece and the nozzle at some moment before 50µs.

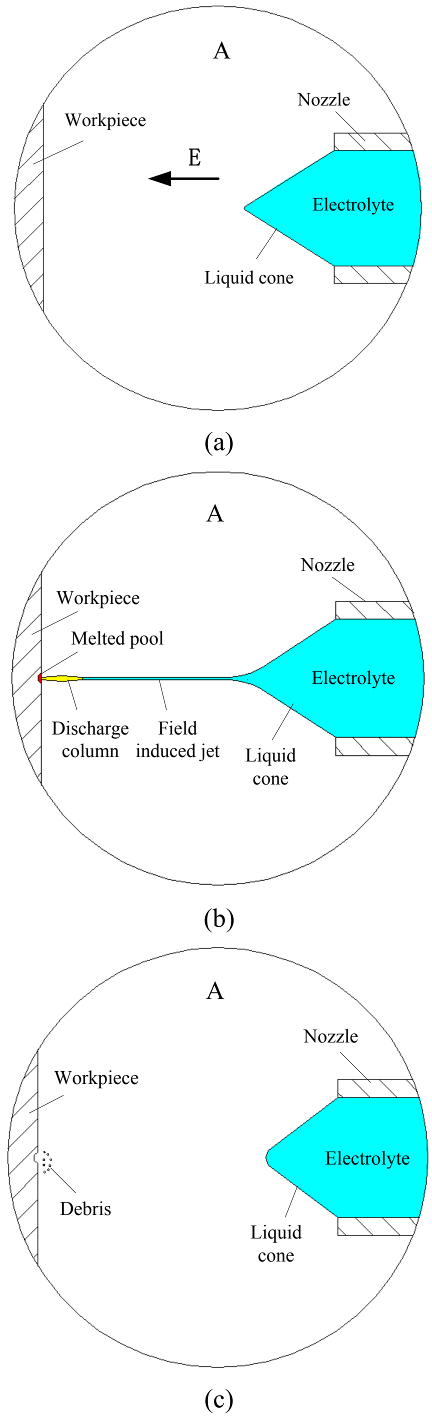


Fig. 2: Principle of field induced jet micro-EDM

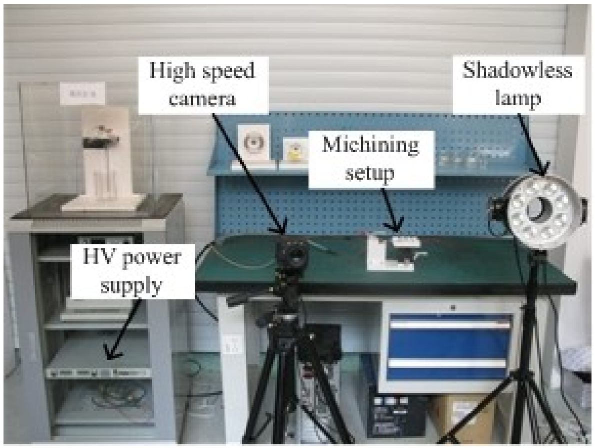


Fig. 3: Observation system of field induced jet micro discharge

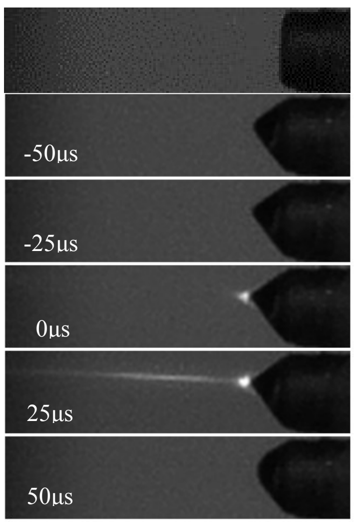


Fig. 4: The evolution of the field induced jet micro discharge

The second image depicts that the electrolyte is attracted by the electrostatic force and the liquid cone tends to be formed while the intense electrostatic field applied upon the nozzle and the workpiece at the moment of -50μs. The tip of the liquid cone shows a rounded shape at the moment. It becomes sharper in the frame of -25μs. At the moment of 0μs a jet stream emitted and a bright spot at the tip of liquid cone can be observed. The image with time stamp of 25μs displays the discharge column while the electrolyte jet stream carrying electrical charge approaches the surface of the workpiece, resulting in an electrical discharge. Twenty five microseconds later, the electrolyte jet stream collapses due to the explosive discharge, and the liquid cone turns into rounded shape by the effect of surface tension. It should be noticed that the field induced jet micro discharge is a periodical process. Although the jet stream collapses during the discharge, it will be generated again in the next cycle.

According to the pixels occupied by the jet stream in the frame of 25μs, the diameter of the jet stream can be estimated as less than 20μm. Apparently, the cycle time of each field induced jet micro discharge is shorter than 50μs under the experimental condition. Thus, the volume of each emission is very small. On the other hand, as a metal capillary, the nozzle has the capillary effect to the electrolyte. Once the electrolyte lost after the jet emission, it will be supplied automatically from the syringe by the capillary effect without using pump and valves. In other words, the electrolyte in the liquid cone will be kept in equilibrium dynamically.

C. FREQUENCY OF DISCHARGE

As a periodical process, the efficiency of filed induced jet micro-EDM is determined by the frequency of discharge. Therefore, several video records are selected to analyze the frequency of discharge. The frame rate of each video is the same of 20,000 frames per second. The electrical potential difference and the gap between workpiece and nozzle were all the same in the experiments. Fig. 5 shows the trends that the number of discharge increases with the number of frame and the videos were in chronological order.

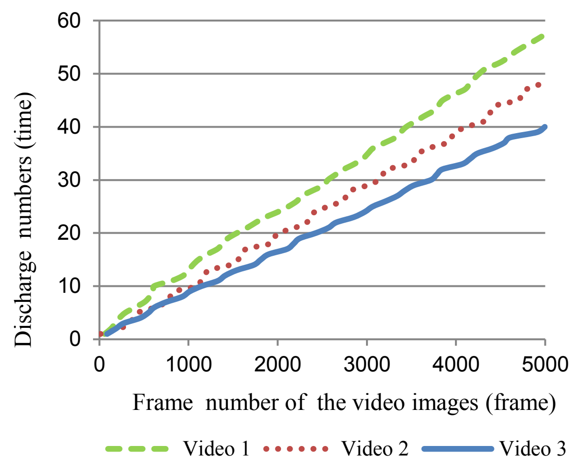


Fig. 5: Number of discharge increases with the number of frame

Obviously, the number of discharge increases uniformly and substantially with the number of frame in the video record. This means that the time interval between two adjacent discharges is relatively even. In other words, the frequency of discharge in each video record is stable and uniform. The slope of the three curves is different with each other: video 1> video 2> video 3. That is caused by the change of humidity in the gap between the workpiece and the nozzle after consecutive field induced jet emissions. The increasing humidity changes the intensity of the electric field, therefore, results in the different discharge frequencies.

According to the frame rate of the videos, it could be estimated that the frequency of discharge ranges from 140 Hz to 250 Hz, which is much lower than the discharge frequency of conventional micro-EDM. So that, the frequency of field induced micro EDM needs to be improved for higher machining efficiency.

It is found that the frequency of discharge could be accelerated through increasing the electric field intensity within a certain range. However, the stability of the liquid cone is affected by the electric field intensity, especially when the electric field intensity exceeded a certain value, the jet stream becomes instable. That is because the dynamic process of the jet stream emission requires continuous supply of the electrolyte from the nozzle and the transmission of electrolyte needs some time. The response speed of the transformation of the liquid cone is governed by the gathering speed of the same charge at the surface of the liquid cone and the viscosity of the electrolyte[9,11]. Therefore, the discharge frequency can be increased by either increasing the electrical conductivity or lowering the viscosity of the electrolyte.

FIELD INDUCED JET MICRO-EDM CHARACTERISTICS

A. MACHINING CONDITIONS

The workpiece material is removed by the energy generated by the periodical field induced jet micro discharge. Therefore, the single discharge has a direct effect on the machining results. A series of field induced jet micro-EDM experiments were carried out in order to get individual single discharge craters on the surface of the workpiece. The size and morphology of single discharge crater also contain information reflects the discharge phenomenon.

Theoretically, field induced jet micro-EDM can be used to process any electrically conductive material. In order to ensure the uniformity of the electric field between the nozzle and the workpiece, the flat workpiece surface with polishing is adopted. The nozzle is aligned in horizontal direction and the workpiece is fixed in the vertical direction respectively. Table 1 lists the machining parameters. The output of high-voltage power supply is set to 3.5 kV at first, and then the gap between the nozzle tip and the workpiece surface is adjusted to 1 mm approximately until the field induced jet discharge phenomenon occurs. The machining process lasts about 2 minutes and then stops.

Table 1: Machining parameters

Inner diameter of nozzle	200μm
High voltage	3.5kV
Nozzle-workpiece Gap	1mm
Material of workpiece	Stainless steel
Electrolyte	Wt 20% $NaNO_3$

To get the single discharge craters, the workpiece needs to be moved in the direction perpendicular to the axis of the nozzle. It was found in the early exploratory experiments that the diameter of a single discharge crater was less than 10μm and the discharge frequency was about 140-250 Hz, thereby the velocity of the workpiece movement should be more than 1.4mm/s, so that the adjacent two sequential single discharge craters would not overlap one after another.

The experimental setup of the field induced jet micro-EDM is shown in Fig. 6. The workpiece and nozzle are connected to the output of the high-voltage DC power supply which can be seen in Fig. 3, while the polarity of workpiece is positive. The motion platform consists of three mini stages, which can be operated manually. The mini stage could also be replaced by electrically controlled stage.

B. MACHINING RESULTS AND ANALYSIS

Scanning electron microscope was used to observe the single discharge craters on the machined workpiece surface. As shown in Fig. 7, the magnification for Fig. 7(a) and Fig. 7(b) are 6,000 and 5,000 respectively. The unit scales of them are both 1μm. It can be seen that there is a deep pin hole in the middle of the crater with a relatively flat and annular molten recast area around it. The diameter of the pin hole is about 2μm.

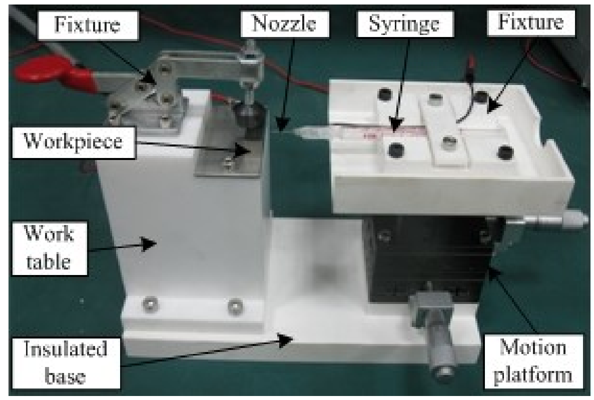
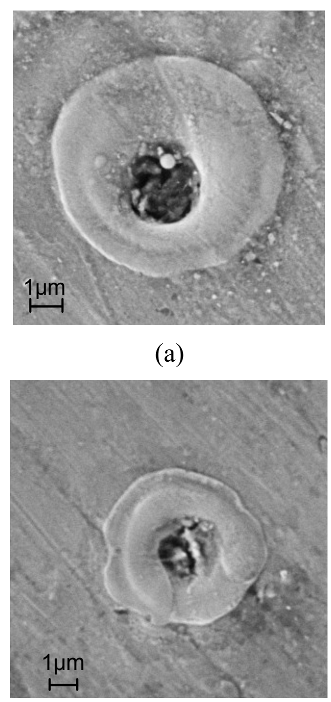


Fig. 6: Experimental setup of field induced jet micro-EDM

The diameter of field induced jet generated by highly conducting liquid can be as small as tens of nanometers[12,13]. It implies that if the diameter of the field induced jet and the energy generated by single discharge could both be controlled precisely and become sufficiently small, the field induced jet micro-EDM might be capable of doing nano meter scale machining.



(a)

(b)

Fig. 7: Morphology of single discharge craters

CONCLUSIONS

A novel micro-EDM process using the extremely fine field induced jet as the micro tool electrode was developed. The preliminary experimental results show that the field induced jet micro-EDM is a periodical process and the frequency of discharge ranges from 140 Hz to 250 Hz.

(1) The diameter of the field induced jet is much smaller than that of inner diameter of the nozzle, therefore, ultrafine jet can be generated by a nozzle with relatively larger inner diameter.
(2) The machining process will immediately occur right after the jet is generated, this avoids the problem of installation error or deformation error of the tool electrode.
(3) Electrolyte can be supplied automatically by the capillary effect and the electric field, there is no electrode wear and its compensation problems.
(4) The discharge occurs only between the front end of the field induced jet and the workpiece surface, therefore the nozzle does not wear out.

Although the field induced jet micro-EDM is an effective micromachining method, its discharge frequency needs further improvement to enhance the machining efficiency. The extensive investigation into the machining characteristics of various electrically conductive materials is remained for the future work.

ACKNOWLEDGMENT

This research is supported by the National Natural Science Foundation of China (Grant No. 51175336).

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