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A study on the machining of high-aspect ratio micro-structures using micro-EDM

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Abstract

Micro-electro-discharge machining (micro-EDM or μ-EDM) has been gaining popularity as a new alternative method to fabricate micro-structures. The main advantages of the micro-EDM method are its low set-up cost, high accuracy and large design freedom. Compared to etching or deposition techniques, micro-EDM has the advantage of being able to fabricate complex three-dimensional shapes with high-aspect ratio. However, there are many operating parameters that affect the micro-EDM process. The fabrication of micro-electrodes on the machine is also an important process to remove the clamping error to maintain high accuracy in the machined micro-structures.

In this paper, the machining of micro-structures is divided into two basic processes. One is the on-machine fabrication of the micro-electrodes with high-aspect ratio, and the other is the EDM of the workpiece in micrometer range. An optical sensor has been developed to measure and control the dimension of the thin electrode during the tool fabrication process. Different methods have been investigated to fabricate a thin electrode into the desired dimension without deflection. The performance of the micro-EDM process is evaluated in terms of the material removal rate (MRR), tool wear ratio (TWR), and the stability of the machining. Influences of the various operating parameters of the micro-EDM process, such as the operating voltage, gap control algorithm, and resistance and capacitance values in the *R–C* spark control circuit, are discussed.

Keywords: Micro-EDM; Electro-discharge machining; Micro-structure; High-aspect ratio; On-machine measurement

1. Introduction

Micro-machining is gaining popularity due to the recent advancements in micro-electro mechanical systems. Many studies have been carried out to fabricate functional micro-structures and components. Micro-machining technology using photolithography on silicon substrate is one of the key processes to fabricate the micro-structures. However, there are some limitations in this process due to its quasi-three-dimensional structure, its low aspect ratio and limitation of the working material. Deep X-ray lithography using synchrotron radiation beam (LIGA process) and focused-ion beam machining process can produce high-aspect ratio three-dimensional sub-micron structures with very high form accuracy. But, these processes require special facilities, and the maximum thickness is relatively small [1,2].

Conventional material removal processes, such as turning, milling and grinding, are also studied to fabricate micro-structures by introducing a single point diamond cutter or very fine grit sized grinding wheels. These material removal processes can machine almost every material such as metals, plastics and semiconductors. There is also no limitation in machining shape, so that flat surfaces, arbitral curvatures and long shafts can be machined, which are required for the moving parts and guiding structures [3,4].

On the other hand, a micro-mould cavity is also needed for mass-production of micro-components, which can be made by injection molding process. Hard-to-machine workpiece materials should be machined very precisely in three-dimensional forms in the micron range for the purpose of micro-injection. For the fabrication of complex three-dimensional molds using very tough die materials, micro-electro-discharge machining (micro-EDM) is one of the alternative machining processes that can be used successfully. Micro-EDM can machine almost every conductive material, regardless of its hardness. Using a very thin electrode with control of the EDM contour, micro-molds can be produced successfully. Although these methods cannot reach the dimensional magnitudes of photo fabrication techniques, such magnitudes are not required in many cases. Besides these, the set-up cost for the photo fabrication and

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etching techniques are also comparatively more expensive than micro-machining using machine tools.

Many studies have been conducted for micro-EDM processes. One of the first experiments reported on micro-EDM was performed by Van Ossenbruggen [5] in the Philips Research Laboratory at the end of 1960s. With a precision EDM machine he was able to fabricate parts with dimensional tolerances of 0.5 μm and with a high-speed EDM method. He was also able to obtain dimensional tolerances up to 1.5 μm with a machining rate of $5\,mm^3\,min^{-1}$. The smallest electrode fabricated had a diameter of 30 μm. Another researcher, Sato et al. [6] was then the first to report on EDM-drilled micro-holes for ink-jet nozzles of printers. The micro-holes have a diameter of 15–300 μm, a roundness of 0.5 μm or better, and a surface roughness of 0.1 μm R_{max}. Soon after, Masuzawa et al. [7] presented a system for drilling deep micro-holes by EDM. The electrodes used had a diameter of less than 50 μm and have aspect ratio of 10:1. From this basic technique, he then derived a three-dimensional micro-machining technology demonstrated by the machining of a rotor for a micro-turbine. The smallest electrodes have a diameter of 4.3 μm for a length of 50 μm. By combining EDM with electro-forming, he was able to set-up a process for micro-nozzle fabrication [8]. Micro-EDM can also be used to machine less conventional materials. It was reported that Toshiba manufactured the magnet of an ultra-small electromagnetic motor with an outside diameter of 3 mm using EDM. In USA, Jacobson used micro-EDM to produce a micro-wobble motor [9].

Even though many research results show successful fabrication examples at micrometer size, the thickness of the machined shape is almost similar to their size. It means that the aspect ratio of a micro-component in current state is usually close to 1. However, there can be requirements to fabricate higher aspect ratio micro-structures using micro-EDM. To increase the aspect ratio of micro-fabrication, longer and thinner tool–electrode is required, and high tool wear rate is to be endured. Careful tool preparation and optimal machining conditions are needed for a high-aspect ratio machining of micro-structure.

This paper presents an attempt to fabricate high-aspect ratio micro-structures on an aluminum workpiece. The machining of micro-structures is divided into two basic processes. One is the on-machine fabrication of micro-electrode tools with high-aspect ratio, and the other is the EDM of the workpiece in the micrometer range. Different methods have been investigated to fabricate a thin electrode into the desired dimension without deflection. The performance of the micro-EDM process is evaluated in terms of the material removal rate (MRR), tool wear ratio (TWR), and the stability of the machining. Influences of the various operating parameters of the micro-EDM process, such as the operating voltage, gap control algorithm, and resistance and capacitance values in the *R–C* spark control circuit, are discussed.

2. High-aspect ratio micro-EDM

Micro-EDM is a non-traditional machining technology that has been found to be one of the most efficient technologies for fabricating micro-components. The non-contact process requires little force between electrode and workpiece and is capable of machining ductile, brittle or super hardened-materials. With appropriate parameters, it is possible for micro-EDM to achieve high precision and high quality machining.

The non-contact nature of EDM makes it possible to use a very long and thin electrode for the machining. Even though a micro-milling cutter of down to 50 μm in diameter is available in the market, the length of the tool is usually 3–5 times of its diameter and it is also not suitable to machine a very tough die material, which only can be machined using EDM. Although micro-EDM plays an important role in the field of micro-machining, it has disadvantages such as high electrode wear ratio and low MRR. The wear of electrode must be compensated either by changing the electrode or by preparing longer electrode from the beginning or fabricating the electrode in situ for further machining. It is not recommended to change the micro-electrode during machining,

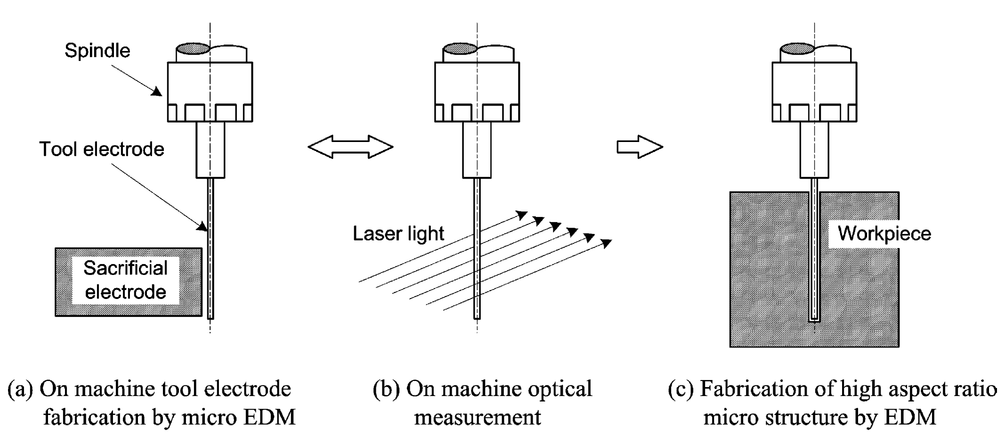


Fig. 1. Process to fabricate high-aspect ratio micro-structures using micro-EDM.

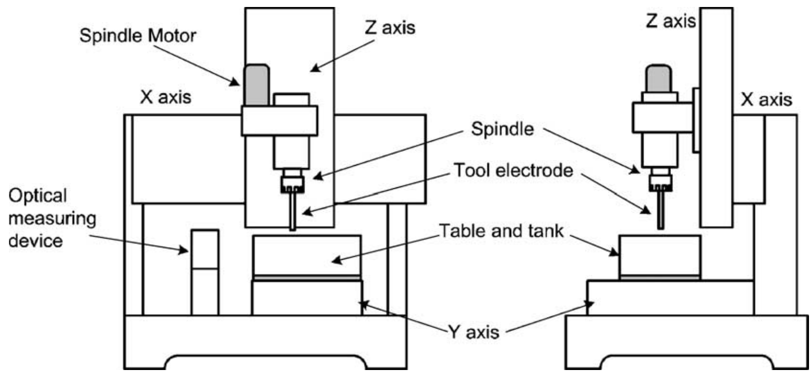


Fig. 2. Structure of desk-top miniature machine tool.

because it may reduce the accuracy due to the change in set-up or re-clamping of the micro-electrode.

Fig. 1 shows a conceptual process to fabricate a high-aspect ratio micro-structures using micro-EDM. In the micro-EDM process, the tool–electrode is fabricated on the machine to avoid clamping error. From an electrode thicker than the required diameter, a cylindrical electrode is fabricated by EDM process using a sacrificial electrode. Different set-up of the sacrificial electrode can be used in this process (Fig. 1(a)). When there is a dimensional change in the sacrificial electrode, the diameter of the tool–electrode fabricated is usually unpredictable. An on-machine measurement of the tool–electrode diameter is required in this case (Fig. 1(b)). An optical measurement device has been specially developed for the measurement of a thin electrode, which consists of a laser diode, optical filter and photo detectors. After measuring the diameter, a compensated machining schedule for the tool–electrode fabrication is generated and machining is carried out. These processes are repeated until the required tool–electrode diameter is achieved. After finishing the tool–electrode fabrication, micro-EDM is performed to fabricate the high-aspect ratio micro-structure (Fig. 1(c)).

3. Experimental set-up and method

3.1. Construction of a multi-purpose miniature machine tool

A multi-purpose miniature machine tool has been developed for high precision micro-machining [10]. Fig. 2 shows the structure of the desk-top miniature machine tool. The machine tool has its size of 560 mm (W) × 600 mm (D) × 660 mm (H), and the maximum travel range are 210 mm (X) × 110 mm (Y) × 110 mm (Z). Each axis has optical linear scale with the resolution of 0.1 μm, and full closed feedback control ensures accuracy of sub-micron. Machine enables changeable high speed, middle speed and low speed spindles for micro-milling, micro-turning and micro-grinding on the machine. The low speed spindle is electrically isolated from the body of the machine so that electrical machining, such as EDM and ECM, can be performed on the machine. The motion controller can execute a program downloaded from the host computer independently; thus a good EDM gap control can be achieved in a real time.

The response of each axis is important because a fast movement is required for the gap control during EDM. Fig. 3 shows the frequency response of the Z-axis with the reference amplitude of 0.1024 mm. The Z-axis shows a linear response up to 10 Hz and a resonant frequency at 100 Hz at the amplitude of 0.1024 mm, which is sufficient distance to control the spark gap in the micro-EDM process. From the characteristic of the Z-axis response, the 0.01 s average gap voltage is used as a feedback signal to control the micro-EDM spark gap.

3.2. Experimental method

The machining process study is divided into two stages. The first concerns the on-machine tool–electrode fabrication process, and the second is on the parameters that affect the EDM and to fabricate a micro-slot on an aluminum block.

In the study of the tool–electrode fabrication process, three different sacrificial electrodes are tested to compare their capability and performance. Fig. 4 shows the three different types of sacrificial electrodes. Fig. 4(a) shows a stationary block, which is the simplest method to machine

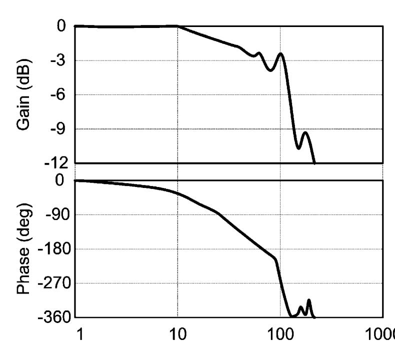


Fig. 3. Frequency characteristics of the Z-axis.

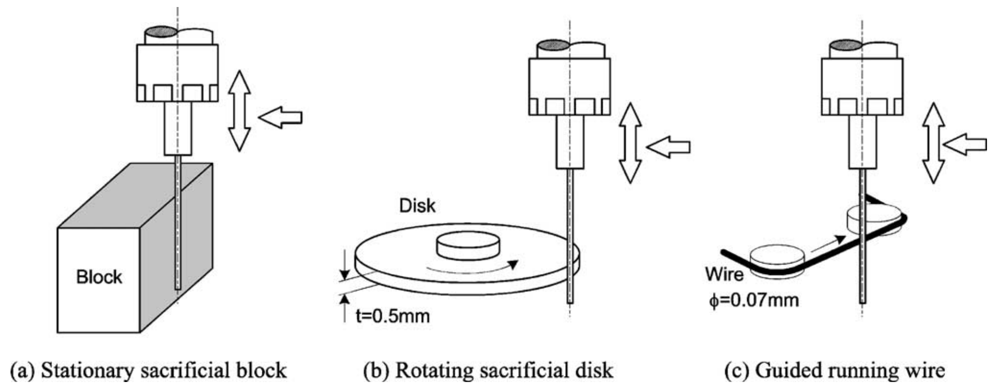


Fig. 4. Three types of sacrificial electrode for on-machine tool fabrication.

a tool–electrode. Fig. 4(b) shows a rotating electrode with 0.5 mm in thickness and 60 mm in diameter. The rotating speed of the disk electrode is about 90 rpm during tool fabrication. Fig. 4(c) shows a guided running wire as a sacrificial electrode of 0.07 mm in diameter. The wire running speed is about 3–5 mm/s. This method is known as wire electro-discharge grinding (WEDG), and it is a typical method for micro-EDM. During the tool fabrication process, the spindle is rotating about 300 rpm and it moves up and down according to the tool–electrode contact conditions. This means that the spindle is under control to maintain the EDM spark gap. Once the tool reaches one end of its stroke movement, the tool moves toward the electrode to a given depth of cut, and the process is repeated.

In this study the characteristics of the micro-EDM is investigated by engraving grooves on the surface of the workpiece. To engrave the groove, the machine tool moves in X–Y plane at a given constant speed while the Z-axis position is controlled to maintain the spark gap as shown in Fig. 5. To maintain continuous spark in between the electrode and workpiece, the speed of the Z-axis is controlled based on the following equation:

$$F_Z = k\,\mathrm{sgn}[V_{\mathrm{gap}} - V_{\mathrm{th}}] \quad (1)$$

where F_Z is the Z-axis feed rate, V_{gap} the gap voltage between the electrode and workpiece and V_{th} the threshold value for the gap control. k is a control parameter that determines the speed of the micro-EDM gap control. The

Table 1
Experimental conditions for micro-EDM

Supply voltage (V)	100–300
EDM circuit	*R–C*, *R–C* with transistor 220
Resistance (Ω)	470, 1k, 4, 7k
Capacitance	100 pF, 470 pF, 1 nF, 4.7 nF, 10 nF
Feed rate (mm/s)	0.1, 0.2, 0.5, 1.0
Spindle speed (rpm)	500
EDM control, k (mm/s)	0.003–0.06
Dielectric coolant	DI water

feed rate of the machine along the X-axis, resistance, capacitance, and gap control parameter k are changed in the micro-EDM evaluation tests. Experimental conditions for the micro-EDM are listed in Table 1.

For the actual machining of a micro-structure, a triangular micro-slot is selected as the target shape in this study. The target dimension of the triangular slot is 3.5 mm × 3.5 mm and the thickness is 0.15 mm as shown in Fig. 6(a). This slot is designed for use in instrumentation to measure a crack. In machining the micro-slot, a linear scanning EDM control approach is used as shown in Fig. 6(b). The feed rate of the tool is given similar to Eq. (1) (Fig. 6)

$$f = k\,\mathrm{sgn}[V_{\mathrm{gap}} - V_{\mathrm{th}}] \quad (2)$$

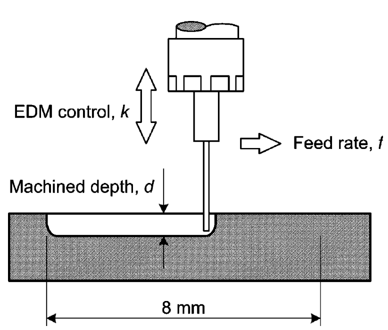


Fig. 5. Surface engraving EDM.

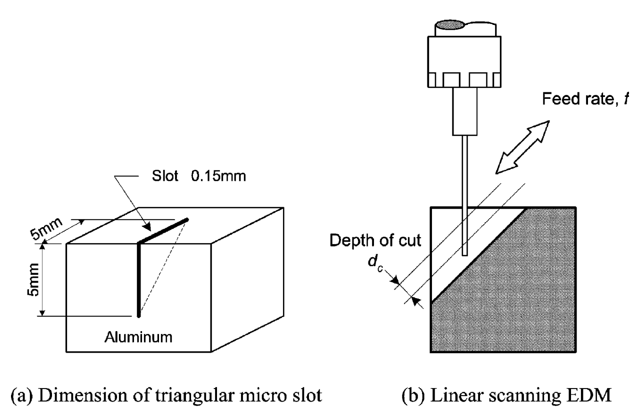


Fig. 6. Fabrication of a triangular micro-slot using linear scanning EDM.

Table 2
Properties of the material

	Workpiece	Tool
Composition	93.5% Al, 4.4% Cu, 1.5% Mg, 0.6% Mn	99.9% W (Ø0.2–0.5 mm)
Density (g/cm^3)	2.7	19.3
Melting point (°C)	658	3370
Specific resistance (μΩ mm)	27.4–27.8	56.5

The properties of the workpiece material and tool material are summarized in Table 2.

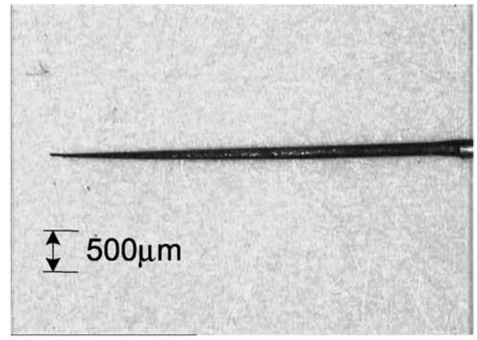
4. Results and discussions

4.1. Effects of sacrificial electrode on the tool–electrode fabrication

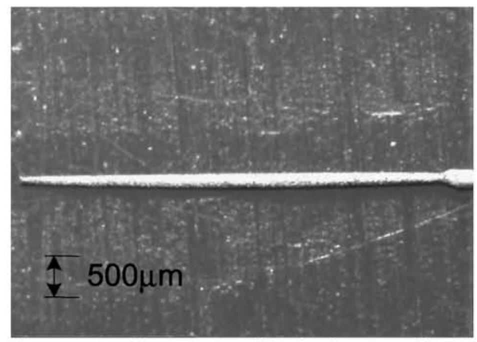
Fig. 7 shows some typical electrode shapes which are fabricated using micro-EDM with different types of sacrificial electrodes. Fig. 7(a) shows the tool–electrode machined using a stationary copper block. The surface of the fabricated tool–electrode is generally smooth. However, the shape accuracy is not as good as desired, and the tool usually has some taper. The tapered shape on the tool–electrode is due to the wear of the sacrificial electrode. Since the tool moves upward and downward during tool fabrication, the lower (tip) portion has a greater chance to face the sacrificial electrode, and consequently is subjected to more discharges therefore machining. Slight tilting of the electrode block toward the tool–electrode does not help to improve the tapered shape. The electrode still has uneven diameter as shown in Fig. 7(b). The stationary sacrificial block electrode is easy to install; however, the shape and dimensions are not easy to control.

Fig. 7(c) shows an example of tool–electrode fabrication using a rotating sacrificial electrode. In this example, there is erosion on the rotating electrode by electrical discharges during machining. However, the erosion is distributed almost uniformly over the whole perimeter of the electrode. Taking into consideration of the diameter difference between the tool–electrode and sacrificial electrode, the dimensional change of the rotating electrode is almost negligible in the tool–electrode fabrication using micro-EDM. The 0.5 mm thickness of the rotating electrode gives the same effect as stationary electrode on the surface finish, since it is wide enough to finish a smooth surface.

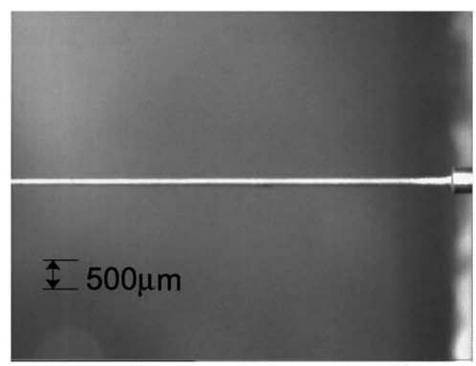
Fig. 7(d) is a typical surface condition of the tool–electrode which is machined by EDM using a running wire. This process is known as WEDG, and is being used widely for micro-EDM machining. Since a fresh wire is continuously used, the dimensional change of the sacrificial electrode is theoretically zero. This fact ensures high-accuracy dimensional control in micro-EDM. However, the surface finishing efficiency is not as high as that of the rotating electrode method. This is due to the fact that the diameter



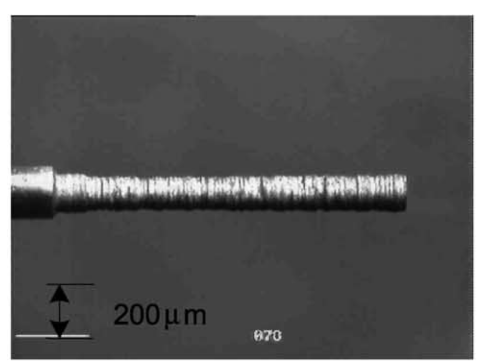
(a) Tapered tool electrode machined using a stationary sacrificial block



(b) Un even diameter machined using a stationary sacrificial block



(c) Electrode machined using rotating disk



(d) Electrode machined using running wire

Fig. 7. Typical shape of on-machine fabricated tool–electrodes.

of the running wire is only 0.07 mm and it is not enough to finish the machined surface smoothly using the same condition of EDM gap control used for rotating electrode. To achieve better surface using this thin wire, the speed of the finishing process must be reduced.

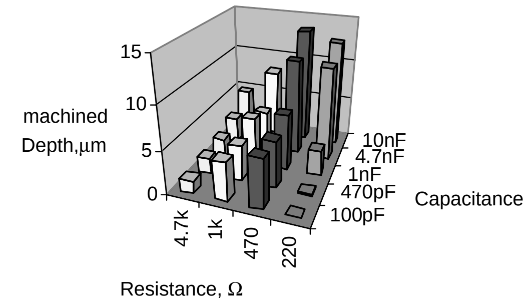
From the comparison of the three different methods, the rotating electrode method is found to be the most efficient method to fabricate a tool–electrode. Even though the wear of rotating electrode is not zero, the diameter of the electrode can be controlled using on-machine measurement followed by compensation-machining.

4.2. Characteristics of micro-scanning EDM with a thin electrode

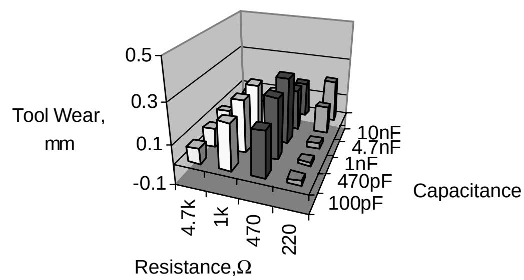
Using a thin electrode first fabricated on-the machine, micro-EDM experiments were conducted and the characteristics of the micro-scanning EDM are investigated. In this study, the surface engraving EDM method is selected where electrode moves along *X*–*Y* plane while *Z*-axis controls the spark gap. Three parameters are changed to investigate their influence on EDM performance. For every EDM experiment, a groove was fabricated and the depth of the machined groove was measured to evaluate the material removal performance. The tool–electrode length was measured to evaluate the electrode wear.

Fig. 8 shows the influence of feed rate in scanning EDM. The EDM control speed *k* is 0.01 mm/s and supply voltage is 100 V. The resistance and capacitance in EDM circuit is 470 Ω and 1000 pF, respectively. As shown in the figure, the machined depth decreases as feed rate increases. When the feed rate is 0.1 mm/s, machined depth is about 10 μm, and this is decreased to 1.2 μm when the feed rate increases to 1.0 mm/s. The tool wear also shows a similar behavior to the machining depth. This is because of the fact that when the feed rate is low, the tool moves slowly and this may cause more electrode wear as more EDM sparks occur at the same position on the workpiece.

The influences of resistance and capacitance on the machined depth and tool wear are shown in Fig. 9. The supply voltage is 100 V, feed rate is 0.1 mm/s and EDM control speed is 0.01 mm/s for these experiments.



(a) EDM circuit effect on machined depth



(b) EDM circuit effect ool electrode wear

Fig. 9. Influence of EDM circuit values.

In Fig. 9(a), it is observed that more material is removed as capacitance value increases. But when the resistance value is 4.7 kΩ, the MRR is relatively small compared to other resistance values. When resistance is 220 Ω and capacitance is smaller than 1 nF, it is very difficult to generate an electrical spark and there is hardly any machining. MRR is relatively high and machining is stable for the range of 470 Ω to 1 kΩ resistance value. Fig. 9(b) shows the wear of tool–electrode. Tool wear shows similar behavior as MRR for various resistance values. But when the resistance is between 470 Ω and 1 kΩ and capacitance is more than 4.7 nF, tool wear is reduced and the micro-EDM shows the best machining performance.

Another parameter for the scanning micro-EDM is the gap control speed to maintain continuous sparking. Fig. 10 shows the machined depth and tool wear with the change of EDM gap control speed *k*. The feed rate is 0.1 mm/s,

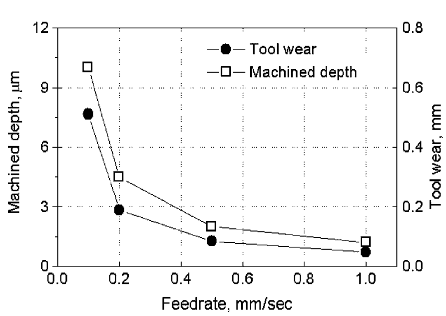


Fig. 8. Influence of feed rate on micro-EDM.

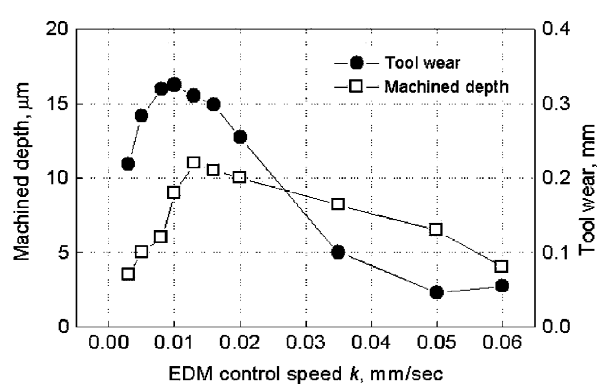
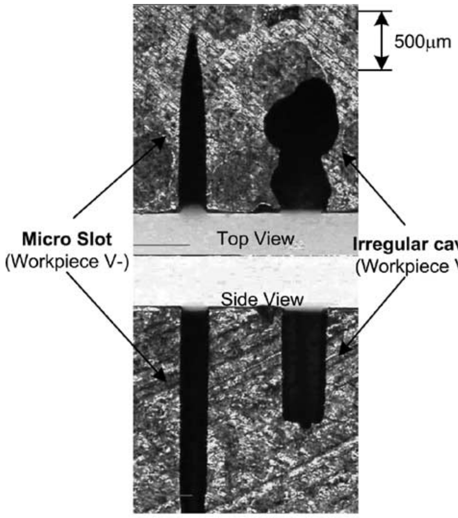
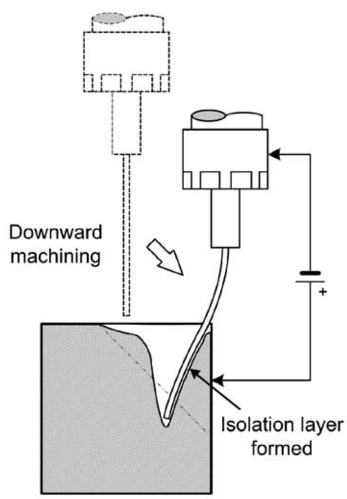


Fig. 10. Influence of EDM gap control.



(a) Failure of micro slot machining



(b) Deflection of electrode in downward machining (workpiece positive)

Fig. 11. Failure of machining using thin tool–electrode.

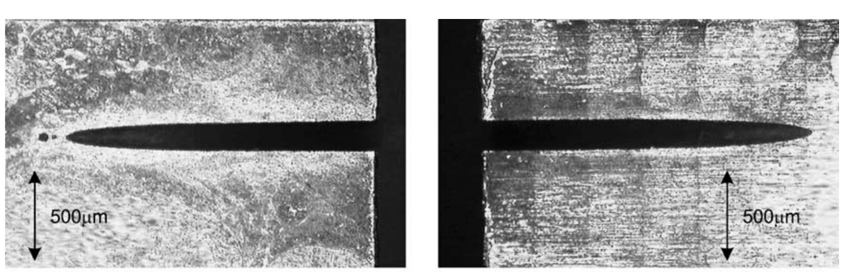
supply voltage is 100 V and capacitance and resistance are 1000 pF and 470 Ω, respectively. The machined depth shows the maximum value when the EDM gap control speed is about 0.013–0.02 mm/s and the material removal is about 10 μm in depth. Together with the change of the material removal, tool wear also shows similar behavior as EDM gap control speed changes. It is observed that when the gap control speed is less than 0.1 mm/s, there are fewer the EDM sparks due to the fast tool wear and it increases the gap between the electrode and workpiece. On the other hand, when the control speed is higher than 0.3 mm/s, the electrode tends to contact the workpiece, resulting frequent short circuit so the material removal efficiency is decreased. In this study, an EDM gap control of 0.01–0.02 mm/s shows a stable and efficient machining.

4.3. Machining of a triangular micro-slot on an aluminum workpiece

Attempts are made to fabricate triangular micro-slots with a dimension of 3.5 mm × 3.5 mm and width of less than 150 μm on an aluminum block. The linear scanning EDM method is selected for this fabrication. The depth of cut is set to 0.1 mm and two machining directions namely upward and downward directions are tested. In the machining of the micro-slot, the tool length is measured using a reference block electrode after finishing each machining path to compensate the tool–electrode wear.

A failure of machining is experienced as shown in Fig. 11(a). When the tool moves in the downward direction, the tool cannot machine any slot but just to make a deep and irregular cavity on top of the workpiece (right side). It is observed that the tool–electrode is bent, instead of machining the workpiece, due to the low stiffness of the tool–electrode. This phenomenon is found in almost every machining trial, especially when the workpiece is set to be the anode and tool–electrode is set to be the cathode. It is observed that there is a thin insulating layer formed on the machined cavity due to the oxidation of the aluminum workpiece, which is known to form a strong insulation film on its surface when it is oxidized. When an insulation layer is formed, the tool–electrode cannot break it due to its low stiffness. On the other hand, the tool can break the layer on the bottom of the cavity since the axial stiffness is not as small as that of radial direction.

From the observation, it is known that the polarity of the aluminum workpiece in micro-EDM must be set to cathode. Otherwise, an insulating layer will be formed on the



(a) Top surface of the workpiece (b) Edge surface of the workpiece

Fig. 12. Examples of the machined micro-slot.

machined cavity and it will prevent further electro-discharge. In the conventional EDM, the tool–electrode can break the insulating layer. However, this is not possible in micro-EDM, where the stiffness of the tool–electrode is very low. Together with the electric polarity, it is observed that upward machining always gives better result than downward machining. This is due to the fact that any impurity existing in between the tool and workpiece may prevent the EDM machining. Presently, the EDM equipment does not have mean to monitor if the machining is abnormal. Consequently, the tool movement will be continued even when it buckles. In the same situation, upward machining experience only a slight elastic deflection of the tool. It may have greater chance to remove the impurity in the following machining cycles. Fig. 12 shows some micro-slots machined using linear scanning EDM successfully. The polarity of the workpiece is cathode, with upward machining.

5. Conclusions

In this study, an attempt is made to fabricate a high-aspect ratio micro-structure using micro-EDM. At first, a very fine electrode is made on-machine by micro-EDM and then micro-EDM is performed to fabricate a micro-structure using the electrode. A series of tool fabrication and micro-EDM experiments have been carried out and the following conclusions are made:

1. Three different types of sacrificial electrodes have been tested to assess their performance for tool–electrode fabrication. The rotating electrode shows the best performance in the high-aspect ratio tool–electrode fabrication.
2. Parameters of scanning micro-EDM have been investigated and a micro-structure has been fabricated successfully. The machining depth is found to be inversely proportional to the feed rate.
3. For the stable and efficient scanning micro-EDM, a gap control speed of 0.01–0.02 mm/s, resistance of 470–1 kΩ and capacitance of 1–10 nF have been found to be the most suitable ranges.
4. The polarity of aluminum workpiece must be set to cathode in order to prevent the formation of an insulating layer. Upward machining tool path is also desired to prevent a catastrophic tool deflection.

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