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Recent Researches in Micro Electrical Machining

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The demand for micro parts and moulds has been increasing in various fields. Among the various micro machining technologies, micro electrical machining is one of the most widely used because it can be applied for conductive or non-conductive materials. This paper discusses the recent studies that explore many ways to improve micro electrical machining performance. Many researchers proposed ways to improve productivity and accuracy through experimental or analytical studies. The improved-performance trends of micro electrical machining are expected to continue thanks to the miniaturization of manufactured goods in a high-tech industry.

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1. Introduction

As the market of miniaturized products has increased, micro machining technology has become an important issue in the fabrication of micro components. Among micro machining technologies, micro electrical machining technologies such as micro electrical discharge machining (EDM), micro electrochemical machining (ECM), and micro electrochemical discharge machining (ECDM) have been investigated by numerous researchers worldwide because of their exclusive advantages. They can machine hard materials, a difficult task with traditional machining technologies. As these electrical machining technologies are based on a non-contact process between the tool electrode and the workpiece, avoiding the problem of tool deformation or breakage,

Table 1 Micro electrical machining

Type	Machining process	Characteristics
Electro-thermal process	Micro EDM	Conductive materials such as metals, alloys, PCD and carbon nanomaterials Discharge energy of 10^{-6} to 10^{-7} Joules[4]
	Micro ECDM	Non-conductive materials such as glass, quartz and ceramic
Electrochemical process	Micro ECM	Micro machining without tool wear, heat affected zone and burr Ultrashort voltage pulse for micro machining
	Electrochemical etching (ECE)	Protective layer or not DC or long pulse
Hybrid process	EDM + ECM	Rough cut by micro EDM and finish cut by micro ECM Machining time reduction Accuracy and surface quality; the same as micro ECM
	EDM + ECE	Rough cut by micro EDM and finish cut by ECE High aspect ratio thin wall fabrication
	EDM + Laser	Rough cut by laser and finish cut by micro EDM Machining time reduction Accuracy and surface quality; the same as micro EDM
	EDM + Ultrasonic vibration ECM + Ultrasonic vibration	Deep hole machining Machining time reduction
	ECE + Laser	EELM (Electrochemical etching using laser masking) Protective layer produced by laser masking

they are suitable for micro machining which requires very small tools. Recently, hybrid machining combining two or more processes has also attracted great attention because it extends process capability. This paper presents recent researches on micro machining by EDM, ECM, ECDM and hybrid machining. Micro electrical machining processes as well as brief characteristics of them are introduced in Table 1.

2. Micro EDM

EDM (electrical discharge machining) is a non-traditional machining process using spark discharges to melt or vaporize material. It can machine not only metals and alloys but also other electrically conductive materials such as PCD and carbon nanomaterials.[1-3] In micro EDM, discharge energy per single pulse is reduced to achieve small material removal. Because the discharge energy is low and the process requires no physical contact between tool and workpiece, the machining force of micro EDM is negligibly small. Using micro EDM, very precise micro features can be fabricated without difficulty. RC circuit as a pulse generator is preferred in micro EDM because it is easy to obtain a pulse with short discharge duration.[4,5] Kerosene and deionized water as a dielectric fluid are commonly used in micro EDM.

Micro EDM has been a very powerful method in micro machining since WEDG (wire electrodischarge grinding) was developed by Masuzawa et al.[6] WEDG has been widely adopted to fabricate micro tool electrode for micro EDM as well as other processes. Using the continuously provided wire electrode on the wire guide, various convex-shape micro tool electrodes can be machined with high precision.[7]

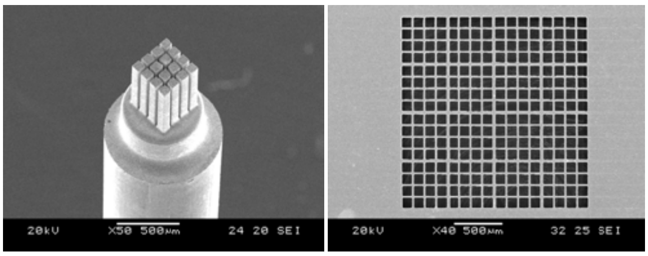


Fig. 1 A 4 × 4 Cu electrode array fabricated by reverse EDM and square holes by micro EDM using the 4 × 4 Cu electrode array. Reprinted with permission[13]

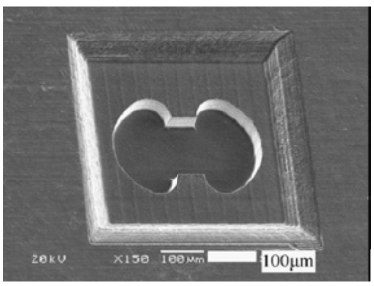


Fig. 2 A complex cavity by micro EDM milling. Reprinted with permission[17]

2.1 Micro EDM drilling and milling

Micro EDM hole drilling has been adopted for various applications including fuel injection nozzles, fiber nozzles and starting holes for wire EDM. Depending on the tool shape, circular or non-circular holes can be machined.[8] As the machining depth increases, appropriate debris ejection and dielectric circulation from the narrow machining gap become difficult. Thus, it is hard to drill deep holes. Deionized water is more suitable than kerosene in deep-hole drilling. This is because deionized water results in higher MRR (material removal rate) and better machining stability because of no carbon generation and large discharge gap.[4,8,9] Various methods such as tool rotation, non-circular tool shape, horizontal EDM system and planetary movement have been attempted for effective debris removal and dielectric circulation.[8,9] Ultrasonic vibration is also suitable for deep-hole machining, and details will be presented in Section 2.3.3.

Compared to serial machining with single tool electrode, machining by micro tool electrode array improves throughput and precision. For this purpose, Takahata et al.[10] used LIGA to fabricate electrode array. 400 Cu cylindrical electrodes with 20 μm diameter and complicated shape electrode array including gear shape were fabricated by LIGA process. With the 400 Cu cylindrical electrodes, machining time was reduced 20~30 times less than serial machining by a single tool. Micro tool electrode array can also be fabricated by other processes such as UV-LIGA,[11] reverse EDM[12,13] and wire EDM.[14,15] In reverse EDM, micro electrode array is machined by micro EDM using a plate with holes as a tool electrode. Fig. 1 shows a 4 × 4 Cu electrode array fabricated by reverse EDM and square holes machined by micro EDM using the electrode array.

Micro EDM milling is used to fabricate 3D micro structures.[16-18] Simple-shape tool electrodes including cylindrical or square shape tools are usually used to follow the designed tool path. Layer by layer process is adopted for the consideration of tool electrode wear and precision. In micro EDM milling, tool electrode wear causes serious inaccuracy. Therefore, many researches on tool wear compensation have been conducted.[17,18] Fig. 2 shows a complex cavity by micro EDM milling with tool wear compensation.

2.2 Micro EDM using water and prevention of electrolytic corrosion

In micro EDM using deionized water instead of kerosene, high machining rate and low tool wear can be achieved.[16,19] However, unwanted excessive removal occurs because of electrochemical reaction (or electrolytic corrosion). The amount of electrochemical reaction differs from workpiece materials. For machining stainless steel, the electrochemical reaction is insignificant because stainless steel has high corrosion resistance. The machining gap was slightly increased and the machined surface covered with pits rather than craters.[16] However, some materials, such as tungsten carbide with cobalt binder, which is widely used as a die/mold material, are very susceptible to electrolytic corrosion during machining. In this case, a large amount of electrolytic corrosion occurs around the machining area and results in surface damage and poor accuracy. When a conventional power supply such as RC type or transistor type is used, the electrolytic corrosion occurs during durations without discharges. This is because there are no sparks, and high positive voltage is applied to the workpiece during the discharge-free time interval. To prevent electrolytic corrosion, studies on power source and dielectric were carried out.[20-22] The workpiece material was tungsten carbide with cobalt binder.

A bipolar pulse with several microsecond pulse duration was used to prevent electrolytic corrosion.[20] The bipolar pulse that has high positive voltage with short duration and low negative voltage with long duration decreases time duration for positive voltage to the workpiece. Therefore, electrolytic corrosion was noticeably reduced in micro EDM drilling. However, the electrolytic corrosion was not prevented completely using a cylindrical tool. Thus, a triangle-shape tool was adopted to prevent the corrosion completely.

To achieve this without any other effort, high frequency bipolar pulse with sub-microsecond pulse duration was used.[21] A new circuit producing a positive pulse of 200 ns and a repetition rate of 1 MHz was developed. During spark discharging, the charged current in the capacitor flows to the machining gap whose mechanism is similar to the conventional RC circuit. High-accuracy holes without the corrosion were machined using this circuit not only in deionized water but also in tap water. Fig. 3 shows a micro hole on WC-Co plate machined by micro EDM using high frequency bipolar pulse in deionized water.

Spray dielectric composed of deionized water and compressed air suppresses the corrosion.[22] The schematic diagram of micro EDM using spray dielectric is shown in Fig. 4. The spray water droplet in the machining gap is not a suitable medium for electrolytic corrosion compared to fluid type. Micro grooves without the corrosion were fabricated by micro EDM milling using the spray dielectric.

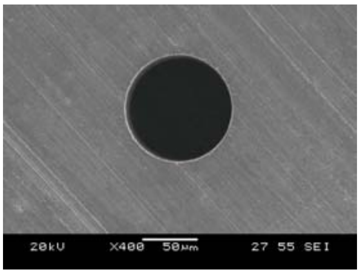


Fig. 3 Micro hole on WC-Co plate machined by micro EDM using high frequency bipolar pulse in deionized water. Reprinted with permission[21]

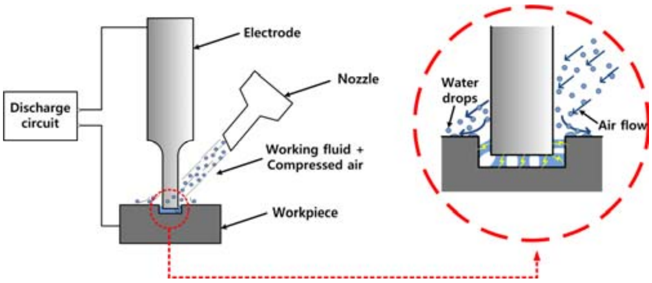


Fig. 4 Schematic diagram of micro EDM using spray dielectric. Reprinted with permission[22]

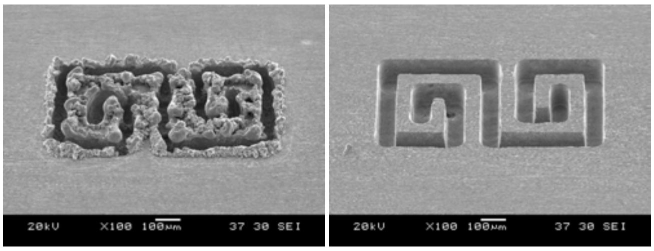
2.3 Hybrid machining: A combination of micro EDM and other processes

2.3.1 Combination of micro EDM and nanosecond pulsed laser

Micro EDM enables high-precision micro structures, while its machining rate is relatively low. In contrast, nanosecond pulsed laser results in a high machining rate with poor accuracy. Kim et al.[23] investigated a hybrid process consisting of pre-machining by nanosecond pulsed laser and post-machining by micro EDM. By using the hybrid process, machining time was reduced and micro structures with high precision were fabricated. In the case of drilling, laser pre-hole helped easier debris removal and dielectric circulation during micro EDM, then machining time was reduced by 90 % compared to micro EDM drilling without pre-hole. In the case of milling, the machining time was reduced by 75 % compared to micro EDM milling. Fig. 5 shows the micro structures after laser pre-machining and after hybrid process.

2.3.2 Combination of micro EDM and micro ECM

Compared to micro EDM, micro ECM (micro electrochemical machining) has no tool wear; therefore, no tool compensation scheme is required. In addition, micro ECM of stainless steel results in fine surface quality. However, the machining rate of micro ECM is quite low. Therefore, the hybrid process composed of rough cut by micro EDM and finish cut by micro ECM was proposed.[24] Micro EDM and ECM used the same machine system except for power source and solution. Therefore, the change from micro EDM system to micro ECM was done without difficulty. Because the electrolyte of micro ECM was a water-based solution (sulfuric acid), deionized water as a dielectric of micro EDM was preferred. The hybrid process allowed fine surface quality and higher machining rate than micro ECM. Fig. 6 shows the micro hemisphere machined by micro



(a) (b)

Fig. 5 Micro structures: (a) after laser pre-machining and (b) after hybrid process. Reprinted with permission[23]

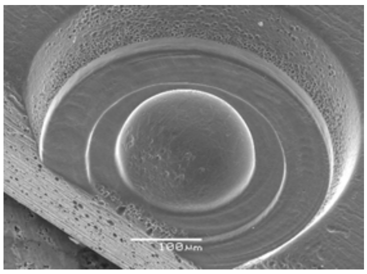


Fig. 6 Micro hemisphere machined by micro EDM/ECM hybrid process. Reprinted with permission[24]

EDM and ECM hybrid process.

In micro EDM/ECM hybrid machining, the use of deionzed water as a dielectric fluid in micro EDM and as an electrolyte in micro ECM has been reported.[25] This process required only an electric power source change, thus efforts and time for the system change were minimized. Also, this is an environmentally friendly process because no toxic electrolyte is used. Using this method, the inner surface of micro EDM holes was finished. The surface roughness was reduced from 0.225 μm R_a after micro EDM to 0.066 μm R_a after finishing.

A combination of micro EDM and electrochemical etching was investigated to fabricate a high aspect ratio stainless steel shadow mask for organic thin film transistors.[26] Square holes were fabricated by micro EDM, and the wall width between holes decreased by electrochemical etching. The thin wall by only micro EDM could not be fabricated due to thermal damage. After two processes, a thin wall with a width of 3.6 μm and an aspect ratio of 26 was fabricated.

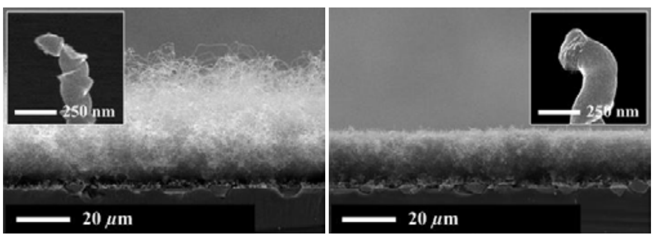
2.3.3 Combination of micro EDM and ultrasonic vibration

Ultrasonic vibration helps debris removal and dielectric circulation from the gap in micro EDM. Thus, a combination of micro EDM and ultrasonic vibration is suitable for deep-hole machining. The ultrasonic vibration was applied to tool electrode,[27] workpiece[28] and dielectric fluid.[29,30] Yu et al.[28] drilled micro holes with an aspect ratio of 29 using ultrasonic vibration of the workpiece and planetary movement. Je et al.[29] reported that ultrasonic vibration of dielectric fluid was also suitable in deep-hole machining and obtained small and deep holes with a diameter of less than 100 μm and an aspect ratio of 23.

In micro EDM drilling, the tapered holes, which have a larger entrance than exit, are produced because of secondary discharges. As the hole depth increases, the taper also increases. To remove the taper, Kim et al.[30] used variable capacitance method in deep-hole machining accompanied by ultrasonic vibration of dielectric fluid. Using the proposed method, a straight hole with a diameter difference of 1 μm between entrance and exit was fabricated.

2.4 Micro EDM of carbon nanomaterials

Carbon nanomaterials such as carbon nanofiber (CNF) and carbon nanotube (CNT) are very attractive materials for various applications including display application. Micro EDM in air was employed for shaping carbon nanomaterials.[3,31] CNFs on the substrate were leveled uniformly or patterned to form lattice structures by micro EDM. It was revealed that carbon nanomaterials were machined efficiently without damage by micro EDM in air. And leveled or patterned CNFs had enhanced field emission uniformity. Fig. 7 shows CNFs before and after micro EDM in air.



(a) (b)

Fig. 7 CNFs: (a) before and (b) after micro EDM in air. Reprinted with permission[31]

3. Micro ECM using ultrashort voltage pulses

3.1 Principle of micro ECM using ultrashort voltage pulses

Electrochemical cell can be usually modeled as an electric circuit, which consists of electrolyte resistance (R_e) and double layer capacitance (C_d). The presence of a charging potential that results from double layer capacitance should be taken into account in micro ECM using ultrashort voltage pulses. Fig. 8 shows the schematic diagram of micro ECM using ultrashort voltage pulse. The charging potential of double layer is exponentially proportional to time constant (τ), which is given by the product of electrolyte resistance and double layer capacitance. Electrolyte resistance is proportional to the distance between tool and workpiece electrode. So, the further region from the tool electrode has a higher time constant. The potential of double layer is inadequate for anodic dissolution. Thus, electrochemical reactions can be localized to the region where the time constant at electrodes does not exceed pulse duration of applied pulse voltage. For micrometer or nanometer resolution, voltage pulses with nanoseconds or picoseconds pulse

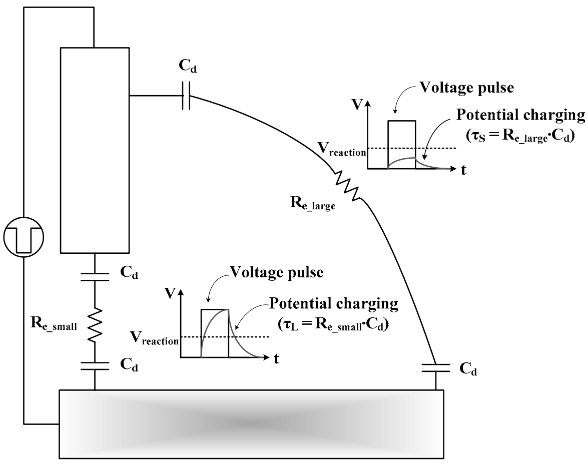
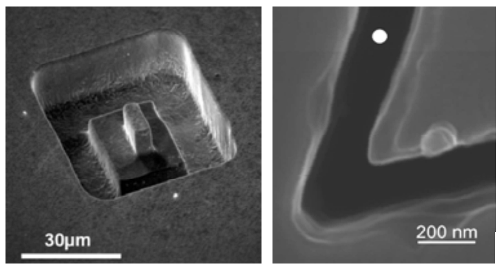


Fig. 8 Electric circuit model in electrochemical cell and charging potential according to time constant in double layer



(a) (b)

Fig. 9 Examples of electrochemical machining: (a) micro machining[33] and (b) nanomachining.[36] Reprinted with permission[33,36] duration have been used.[32-36]

3.2 Drilling and milling in ECM

As shown in Fig. 9, micro or nano machining such as drilling and milling can be performed by ECM using ultrashort voltage pulses.[32-36] A micro hole with Φ 8 μm was machined in micro ECM,[37] and 3D micro structures such as micro groove, slot, semi-sphere, channel and column were fabricated successfully on various materials by micro electrochemical milling.[12,32,33,38]

3.2.1 Methods for improving productivity

The critical drawback to micro ECM is its very slow machining rate. Various methods have been proposed for improving productivity. The micro hole array was machined using multiple electrodes in micro ECM. As shown in Fig. 10(a) and (b), three micro holes of Φ 45 μm were successfully machined simultaneously by three tool electrodes.[38]

As the number of tool electrode increases, the machining area increases. In micro ECM using a few nanoseconds pulse duration, the machining area was limited due to reasons such as impedance mismatching of electrochemical cell and the limitation of charging double layer potential.[39,40] To improve productivity, Park et al. proposed micro ECM by individual pulse generators using a serial MOSFET circuit. Using a serial MOSFET circuit, multiple holes on a stainless steel plate was machined simultaneously by multiple electrodes consisting of 30 single shafts as shown in Fig. 10(c) and (d).[40]

In micro ECM, the dissolution rate decreases as the depth of the hole increases because of electrolyte diffusion and bubble problem. To overcome these problems, a micro hole with a depth of 300 μm was fabricated by micro ECM using the semi-cylindrical-shaped tool with ultrasonic vibrations.[41] It was verified experimentally that the dissolution rate of micro ECM was improved substantially through semi-cylindrical-shaped tool with ultrasonic vibrations.

3.2.2 Methods for taper reduction

In micro ECM, the problem of micro drilling or milling is the generation of taper. Taper shape shall be generated because machining gap increases with dissolution time during anodic dissolution. Taper, which results from the difference in dissolution time, causes deterioration in form accuracy. To prevent taper, researchers proposed a variety of ideas such as machining using disk-type tools and machining using tool insulation. Using these methods, the local machining gap during anodic dissolution is invariable despite the variation of machining depth. Actually, Fig. 11(a) and (b) show disk-type tools and micro columns machined by disk-type tools.[38] As shown in Fig. 11(c) and (d), micro wall with a high aspect ratio was machined by insulated tool electrode.[39]

3.2.3 Micro ECM using various-shape tool electrodes

For fabricating various cut shapes, thin wire can be used as tool electrodes in micro ECM. Unlike wire EDM, wire feeding is not necessary because wire is not worn out in micro wire ECM. So, the diameter of wire in wire ECM is smaller than that of wire in wire EDM. As platinum is substantially stable in electrochemical reaction, platinum wire with Φ 10 μm was used as tool electrode in ECM.[38,42] However, the deformation of platinum wire, which results from low strength can result in decreased machining accuracy. On the other hands, tungsten wire with Φ 10 μm can be used as tool electrode in wire ECM because the mechanical strength of tungsten is higher than that of platinum. Stronger tungsten wire is not easily deformed by a little physical contact and bubbles during electrochemical reactions. As shown in Fig. 12, wire ECM allows the fabrication of precise features such as micro fin, micro gear shape and micro channel.[42,43]

For stable machining, a nickel probe electrode was made by electroforming. In micro ECM, electrochemical cells can be made up of three-electrodes, which consist of tool electrode (cathode),

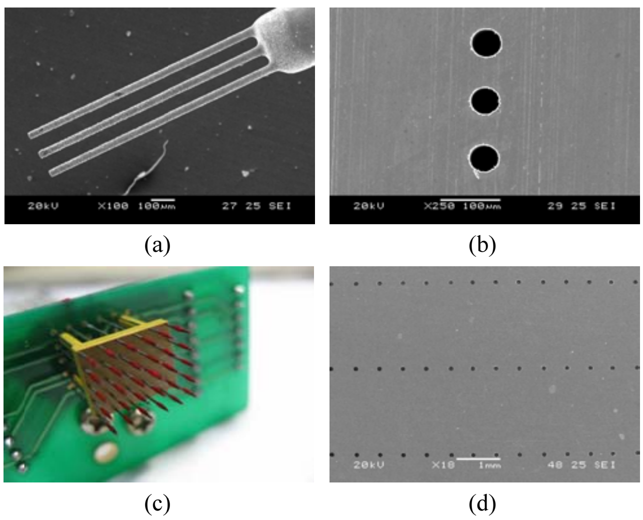


Fig. 10 Micro hole array using multiple tools: (a) multiple electrode by reverse EDM,[38] (b) hole array,[38] (c) multiple insulated tool electrode[40] and (d) hole array by multiple insulated tool electrode.[40] Reprinted with permission[38,40]

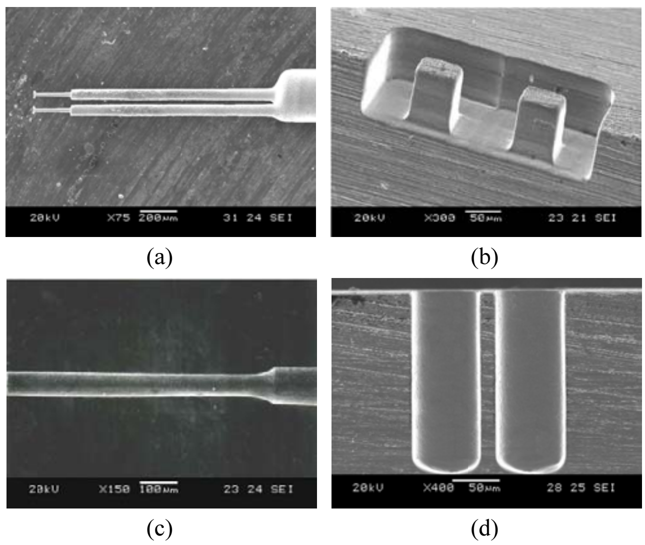


Fig. 11 (a) dual disk-type electrodes,[38] (b) micro columns by disk-type electrode,[38] (c) insulated tool electrode[39] and (d) cross-section view of micro wall by insulated tool.[39] Reprinted with permission[38,39] workpiece electrode (anode) and reference electrode. The reference electrode plays an important role in ECM because the potential difference between two electrodes should be controlled by the reference electrode for stable machining. Specifically, the reference electrode should be close to the machining area to reduce potential error resulting from potential drop. To solve this problem, micro ECM using a nickel probe electrode by electroforming was proposed.[44] The reference electrode can be close to the workpiece during anodic dissolution because a probe-type nickel electrode by electroforming consists of a tool electrode and a reference electrode. Micro groove was fabricated by ECM using nickel probe.

3.2.4 Applications of micro ECM

Micro ECM offers such applications as complex internal structures in a micro hole and surface texturing for friction reduction of machine parts.

The internal features are difficult to fabricate by other machining methods. However, micro internal features can be easily obtained by controlling pulse on-time, pulse amplitude and machining time in ECM. These internal micro features by micro ECM include reverse-tapered hole, barrel-shaped hole, spherical cavity and internal groove in micro hole.[45] Fig. 13(a) shows groove array in micro hole.

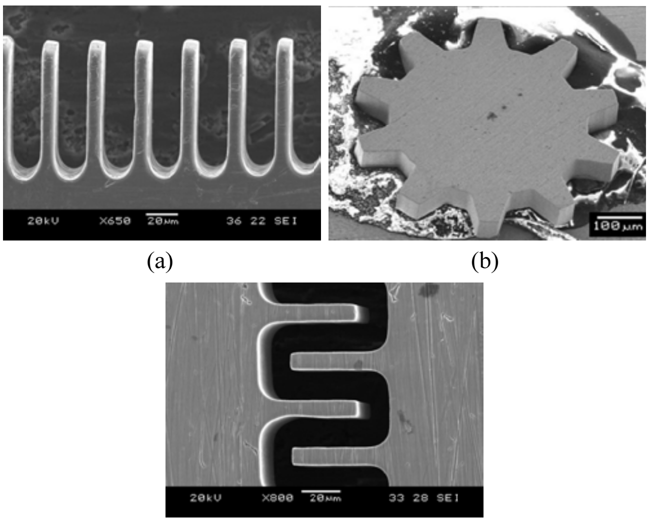


Fig. 12 Micro gear shape and micro channel by wire ECM: (a) micro grooves,[42] (b) micro gear[43] and (c) micro channel.[43] Reprinted with permission[42,43]

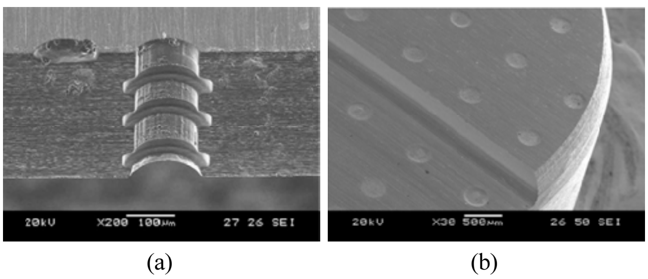


Fig. 13 Applications of micro ECM: (a) groove array in micro hole[45] and (b) dimple pattern on the step-shape workpiece.[46] Reprinted with permission[45,46]

Micro ECM without thermal damage and mechanical damage on the workpiece has some advantages over surface texturing. Byun et al. reported the fabrication of micro dimple pattern by ECM and a successful friction test on a surface-textured workpiece by ECM. Also, as shown in Fig. 13(b), dimple pattern on the step-shape (non-planar surface) workpiece was fabricated.[46] Micro ECM shows great promise in surface texturing.

4. Micro electrochemical etching

Electrochemical etching using DC voltage or long pulse voltage is an alternative method for micro machining with a large area. As mentioned in Chapter 3, the localization of the machining region is difficult in electrochemical etching when using DC voltage or long pulse voltage. Alternative methods such as electrochemical etching using photo-mask, metal anodizing and protective layer by laser masking have been investigated.

4.1 Fabrication of micro tip using electrochemical etching

For micro milling or drilling, a micro-shaft-shape tool is required. The electrochemical etching process is one of the micro fabrication technologies for micro shaft of metal such as tungsten and tungsten carbide.[47-49] Electrochemical etching using DC voltage is a very simple, low-cost method compared to others. As shown in Fig. 14, tungsten carbide (WC) micro shaft (3 mm length, 5 µm diameter and 0.2° taper angle) was fabricated by electrochemical etching.[48] Also, micro hole and groove were machined using micro shaft, which was fabricated by electrochemical etching.[37]

4.2 Micro electrochemical etching using protective layer

In electrochemical etching using photo-lithography process, the workpiece is selectively etched thanks to photoresist mask by fabricating a photo-lithography process. That is, the exposed region on the workpiece is dissolved only with the exception of insulated region by photoresist. Micro features on metal surfaces such as copper, aluminum, titanium and stainless steel were fabricated by electrochemical etching through photoresist mask.[50-52] However, electrochemical etching using photoresist mask has some drawbacks. Photo-lithography for making photoresist mask process requires complex procedures, resist, clean room and expensive devices. It is also difficult to fabricate multilayered structures. Thus, new processes without photoresist mask were proposed. As shown

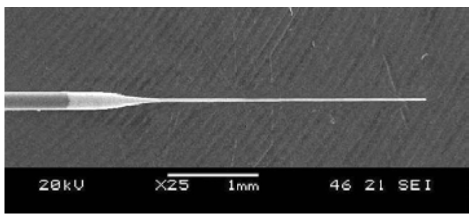


Fig. 14 Tungsten carbide micro shaft by electrochemical etching. Reprinted with permission[48]

in Fig. 15, electrochemical micro machining using oxide film laser lithography (OFLL) was performed for micro machining of titanium.[53] Micro probe array on aluminum was machined by this procedure, which include anodizing, laser irradiation and electrochemical etching.[54]

However, electrochemical etching using anodizing process and maskless laser patterning is limited to valve metal such as titanium and aluminum. On the other hand, electrochemical etching using laser masking (EELM) can be applicable to micro patterning of stainless steel without anodizing process or photo-lithography. From this perspective, the EELM process can become another alternative process. The procedures of EELM consist of laser masking, electrochemical etching and ultrasonic cleaning. As shown

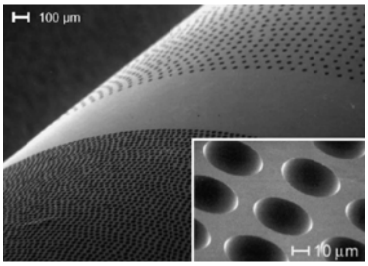
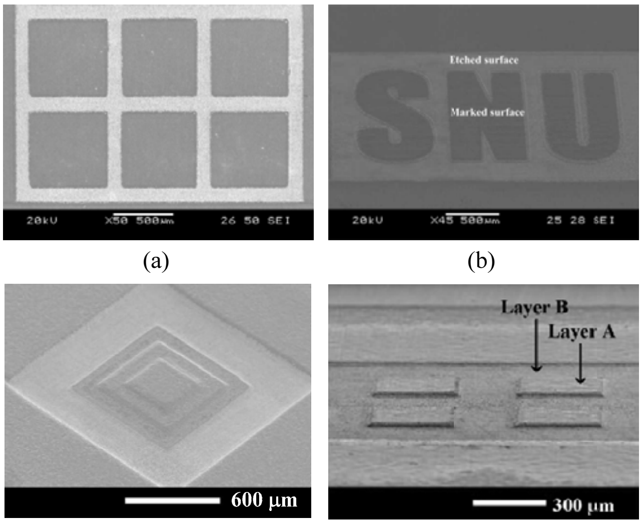


Fig. 15 Micro structured cylinder by OFLL process.[53] Reprinted with permission[53]



(a) (b) (c) (d)

Fig. 16 Micro patterns and structures by EELM process: (a) micro square pattern,[55] (b) embossed characters[55] (c) three storied tower[56] and (d) multilayered structure.[56] Reprinted with permission[55,56]

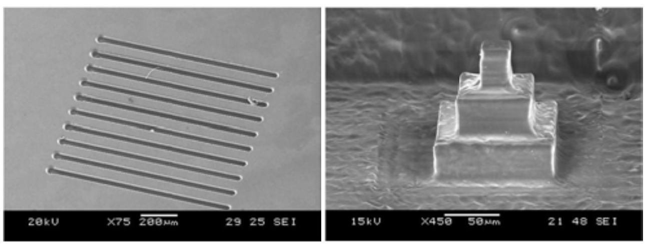


Fig. 17 Micro structures on Pyrex glass by micro ECDM. Reprinted with permission[57]

in Fig. 16, micro patterns and multilayered structures were successfully fabricated on stainless steel by EELM process.[55,56]

5. Micro ECDM

Micro ECDM (micro electrochemical discharge machining) is a machining process based on material removal by electrochemical discharges. When a proper voltage is applied, the tool electrode is covered with hydrogen gas film. Discharges occur between the tool electrode and the surrounding electrolyte. Using this process, non-conductive materials such as glass, quartz and ceramic can be machined. Micro grooves and 3D structures less than 100 μm on Pyrex glass were fabricated with high precision as shown in Fig. 17.[57]

Many researches on improving machining characteristics and extending process capability have been conducted. It was reported that accuracy and surface integrity was improved by using powder mixed electrolyte[58] and pulse voltage.[59] Studies on a combination of ECDM and other processes such as ultrasonic vibration for deep-hole machining[60] and PCD grinding for surface roughness improvement[61] were reported. Wire ECDM,[62] which was similar to wire EDM, was attempted for extending process capability.

6. Conclusions

The recent researches of micro electrical machining such as micro EDM, ECM, ECDM and hybrid machining were reviewed in this paper. Numerous studies on improving machining characteristics as well as applications have been reported. Obviously, micro electrical machining technologies are suitable for the fabrication of micro features including not only holes and grooves but also complicated 3D structures on various materials. The materials include conductive materials such as metals, alloys, PCD and carbon nanomaterials, and non-conductive materials such as glass, quartz and ceramic. These machining processes require micro tool electrode. Because these processes avoid physical contact between tool and workpiece, they can produce high-precision micro features using very small tool electrode without difficulty. Thanks to their exclusive advantages, demands for these machining processes have increased continuously in various industries including electronic, optics, automotive and medical fields.

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