Review International Journal of Electrical Machining, No.12, January 2007

Review on Recent Research in Electrochemical Machining Using Ultra Short Pulses

Bo Hyun Kim[1], Chong Nam Chu[2]
(Received on December 28, 2006)

[1]School of Mechanical Engineering, Andong National University, Andong, Korea
[2]School of Mechanical and Aerospace Engineering, Seoul National University, Seoul, Korea

Abstract

Recently, the use of ultra short pulses of nanosecond duration has changed ECM into promising technology with nanometer resolution. This paper reviewed recent research in nano/micro ECM using ultra short voltage pulses. The mechanism of the process is described and machining parameters, including electrolyte and pulse conditions, are discussed. Applications of micro ECM such as electrochemical drilling, electrochemical milling and wire ECM are described. Machining samples of nano and micro ECM are also presented.

Key words: Electrochemical machining, Micro machining, Ultra short pulse

1. INTRODUCTION

Electrochemical machining (ECM) has been widely used in the manufacturing industry because hard metals can be machined regardless of the mechanical property of a workpiece. However, since the gap between an electrode and the workpiece is large, ECM has not been used for micro machining. In 2000, Schuster et al. showed that the machining gap can be reduced to sub-micrometers by applying ultra short pulses [1]. ECM using ultra short pulses can be used in micro hole drilling, micro milling and wire cutting, where micro electrical discharge machining (EDM) has been applied. Since ECM is based on an electrochemical reaction, it can be applied to nanometer scale machining. Unlike micro EDM, which suffers from tool wear, there is no tool wear in ECM [2]. This characteristic also allows much smaller tool electrodes such as sub-micrometer scale electrodes in ECM [3]. In this paper, recent research about nano/micro ECM using ultra short pulses is reviewed. The principle of the process and the applications of ECM are presented.

2. MICRO ELECTROCHEMICAL MACHINING

2.1. Principle of electrochemical machining with ultra short pulses

When a tool electrode and a workpiece electrode are immersed in electrolyte, a very thin layer called the electrochemical double layer (DL) exists at the interface between the electrode and the electrolyte [4]. Electrochemical reactions are driven by the potential drop across the DL that are similar to two charged layers as shown in Figure 1. As potential is applied between the two electrodes, the potential profile in the double layer becomes similar to that of an equivalent circuit that consists of capacitors and resistors as shown in Figure 2. Since electrolyte resistance (R) is the product of the gap distance (d) between the electrodes and the specific electrolyte resistivity (ρ), the charging time constant (τ) for the double layer of specific capacity (c) is $\tau = \rho c d$. If the gap distance between the tool electrode and the workpiece is small, the time constant for double layer charging is small. If the duration of applied pulses is longer than the time constant, the double layer becomes charged enough for dissolution as shown in Figure 3 [5]. However, in the regions where the time constant is larger than the pulse duration, the double layer is not charged sufficiently for dissolution. Therefore, when a tool electrode approaches a work piece as shown in Figure 4, electrochemical dissolution occurs in the region closest to the electrode end, where the charging time constant is small. Since the chemical reaction rate is exponentially proportional to the potential drop in the double layer, the dissolution area (i.e., the machining resolution) can be controlled by changing pulse duration.

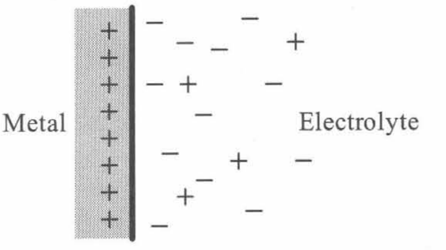


Figure 1. Metal-solution interface

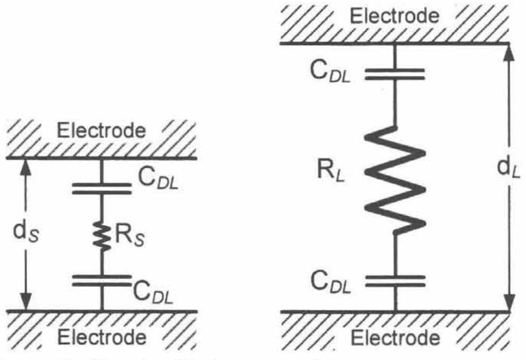


Figure 2. The double layer model

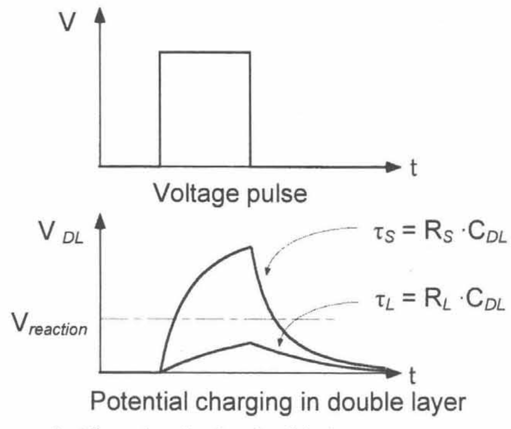


Figure 3. Charging in the double layer

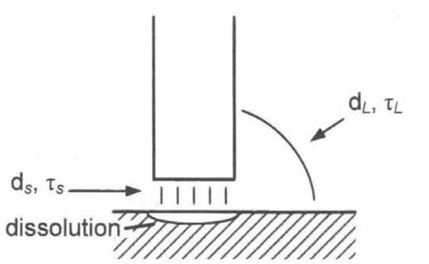


Figure 4. Restriction of electrochemical dissolution

2.2. Experimental system

The experimental system for ECM is shown in Figure 5. It consists of a potentiostat, a pulse generator, an X-Y-Z stage, a tool electrode and a workpiece. The potentiostat controls the potential of the tool electrode and the workpiece to prevent them from passivating. The pulse generator applies positive voltage pulses on the workpiece or negative voltage pulses on the tool electrode. Generally, the pulses, ranging in duration from hundreds of picoseconds to tens of nanoseconds, are required for nano/micro machining. Tool electrode materials such as platinum, tungsten or tungsten carbide, etc. are used. The tool electrodes are made by electrochemical etching, wire electrical discharging grinding (WEDG)[6], and focused ion beam milling. Commercial STM tips or micro wires are also used.

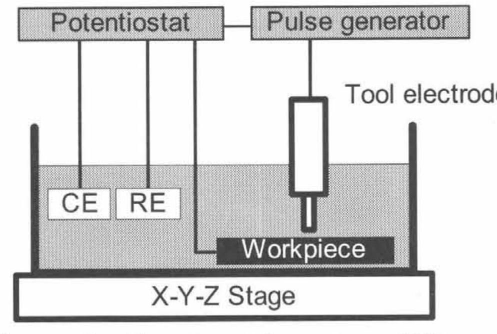


Figure 5. Experimental system (CE: counter electrode, RE: reference electrode)

2.3. Workpiece material

In recent research, the machining of a few materials such as copper, nickel, stainless steel, tungsten carbide, and p-type silicon have been reported [1,2,3,7,8,9]. The examples of the machining are shown in Figure 6.

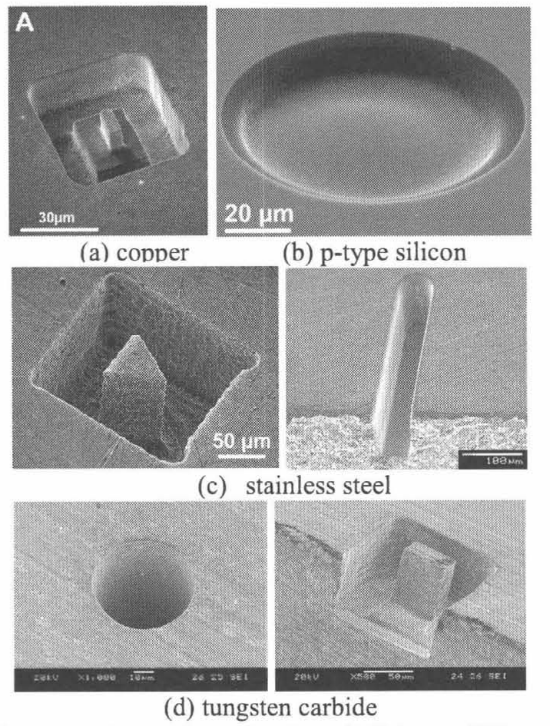


Figure 6. Examples of micro ECM on different materials

According to the workpiece materials, different electrolytes were used. Table 1 shows examples of electrolyte usage for different workpiece materials. The concentration can be changed according to machining resolution. Unlike EDM, which can machine any conductive materials regardless of their mechanical and chemical properties, ECM is based on the electrochemical dissolution of a workpiece. Since electrochemical properties of workpiece materials are different from each other, proper electrolytes and machining conditions vary according to the workpiece material.

Table. 1 Electrolytes used for ECM

Workpiece material	Electrolyte
Copper	0.01 M $HClO_4$ + 0.1 M $CuSO_4$
Nickel	0.5 HCl
Stainless steel	3 M HCl + 6 M HF 0.1 M H_2SO_4
Tungsten carbide	0.5 M $NaNO_3$ + 0.2 M H_2SO_4
p-type silicon	5 M HF + 0.1 M H_2SO_4

2.4. Gap control

For the feed control, average gap voltage is monitored, which is also used in micro EDM. When the tool connects with the workpiece, the average gap voltage is changed, and then the tool moves back. After the gap voltage is recovered, the machining is resumed. More precisely, the gap distance between the tool and the workpiece can be monitored by the current transient. Figure 7 shows the voltage pulse and current [1]. With distances less than 1 μm between the tool and the workpiece, the peaking of the current due to local charging of the DL capacity is shown. Therefore, the gap distance can be controlled by monitoring the height of the current peak.

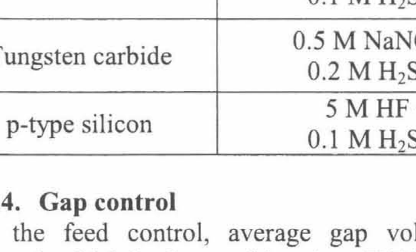
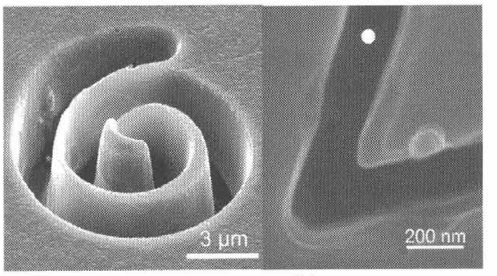


Figure 7. Single voltage pulse (U) applied to the electrodes and resulting current transients (I) for different electrode separations (1. <1 μm; 2. 1 μm; 3. 20 μm).

3. NANO ELECTROCHEMICAL MACHINING

By decreasing the pulse duration up to picoseconds, sub-micro scale machining resolution can be obtained. Indeed, in experiments with a 200 MHz pulse train of 500 ps and 2 V pulses, a machining gap around 80 nm was obtained for the machining of Ni in 0.2 M HCl [3]. Figure 8(a) shows a spiral trough, which was machined with 3 ns pulses. The machining gap between the tool and workpiece is about 600 nm. W tips, similar to scanning tunneling microscope (STM) tips, were used. Figure 8(b) is another example of nano ECM which was machined with picosecond pulses.

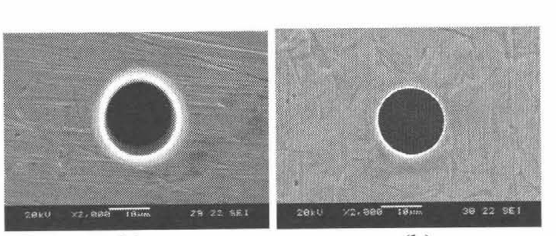


(a) (b)

Figure 8. Nano ECM on nickel: (a) spiral trough with a depth of 5 μm. 33 MHz, 3 ns, 2 V pulses used. (b) 1 μm deep triangular trough. 200 MHz, 500 ps, 2 V pulses used. The white circle indicates the diameter of the tool.

4. MICRO ELECTROCHEMICAL DRILLING

A micro hole is one of the basic elements for micro devices or micro parts. For machining holes with diameters of a few tens of micrometers, there are only a few techniques available such as micro drilling or micro EDM. In these processes, however, the tool wear makes it difficult to machine the hole of a small size with a high aspect ratio. ECM can be applied for the machining of a micro hole with high aspect ratio without tool wear [10]. Figure 9 shows a micro hole with 15 μm diameter, which was machined on a 50 μm thick, stainless steel plate by micro ECM. A micro electrode with an approximate 10 μm diameter was used for the machining, which was fabricated by electrochemical etching. Since the electrode was very flexible, it was easily vibrated by generated bubbles. For suppressing the formation of bubbles and reducing the machining gap, pulse amplitude and pulse on-time were kept as low as possible. Since the machining time at the hole's entrance was longer than that at the hole's exit, the entrance became larger than the exit. Also, it was difficult to get a sharp edge at the hole's entrance because of this.



(a) (b)

Figure 9. Micro hole machined by ECM (a) hole entrance, (b) hole exit (304 SS, Ø 15 μm, 50 μm depth, 5 V, 40 ns, 0.05 μm/sec).

5. MICRO ELECTROCHEMICAL MILLING

Micro ECM was applied to fabricate 3D structures through the electrochemical milling process. For the electrolyte flushing, layer-by-layer machining was applied. With diluted and less toxic electrolytes, 0.1 M H_2SO_4, micro structures with a good surface quality (R_a 0.28 µm) were machined [2]. Figure 10 shows a micro hemisphere on the top of a cylinder. This structure was machined in three steps. For the rough cut, the cylinder was machined and the hemisphere with 100 µm diameter was machined on the cylinder. For the finishing cut, the hemisphere with 60 µm diameter was machined. In the finishing cut, the material was removed with very fast feedrate, 20 µm/s, because the amount of removed material was quite small. Since the feedrate was very high in the finishing cut, the dissolution time decreased and the machining gap could be decreased to only a few µm.

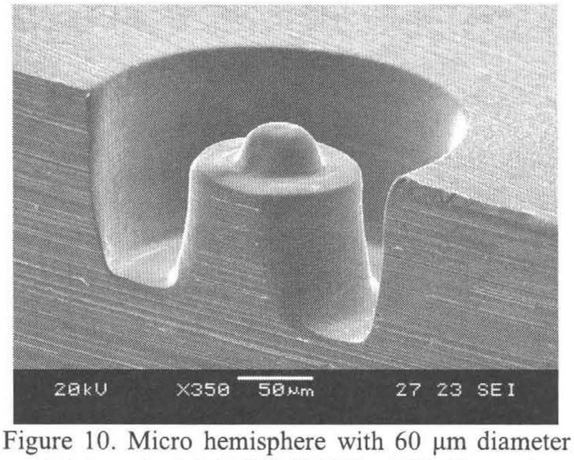


Figure 10. Micro hemisphere with 60 µm diameter on stainless steel (304 SS) (1 MHz, 6 V, 60 ns pulses used).

6. TAPER REDUCTION

6.1. Disk-type electrode

Figure 11 shows that the machining gap increases with the machining time in ECM [2]. The dissolution rate is high in the initial stage of machining, but decreases rapidly after a certain time. The increase in the machining gap causes the taper shape of structures. Figure 12(a) shows that the machining gap increases with an increase in machining depth when a cylindrical electrode is used. The machining gap of the initially machined layer is g_0. However, it increases to g_l during the machining, which causes the tapering of a side wall. Figure 12(b) shows the example of a micro structure that was EC milled with a cylindrical electrode.

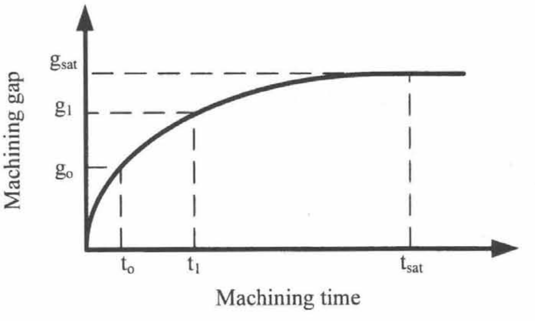
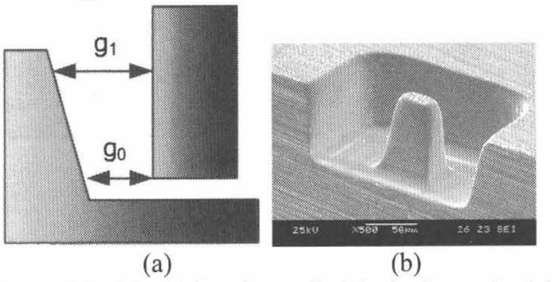


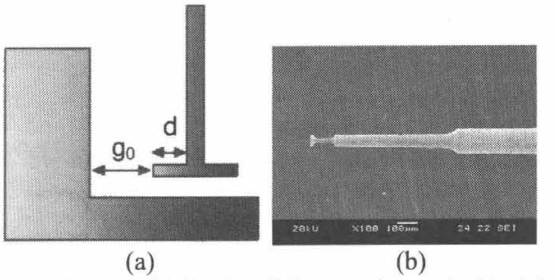
Figure 11. The machining gap according to the machining time.



(a) (b)

Figure 12. Machining by cylindrical electrode (a) side wall profile, (b) micro column (304 SS, 6 V, 60 ns pulse on-time, 1 µs period).

To prevent the dissolution in the tool side, a disk--type electrode was applied. Figure 13(a) shows the side wall profile when the disk-type electrode was used. With the cylindrical electrode, the difference in gaps is (g_l − g_0). If the disk-type electrode is machined such that *d* is larger than (g_l − g_0), then the initial machining gap (g_0) will not increase and the tapering can be reduced. Figure 13(b) is an example of the disk-type electrode that was machined so that d is larger than 10 µm by micro EDM.



(a) (b)

Figure 13. Machining by disk-type electrode (a) side wall profile, (b) disk-type electrode by micro EDM (WC, 54 µm disk diameter, 22 µm neck diameter).

Figure 14 shows an example of the micro column, which was machined with a disk-type electrode. Using the disk-type electrode, 3D micro structures can be machined without tapering. Use of multiple disk-type electrodes increases machining accuracy as well as productivity. The multiple disk-type electrodes were machined by reverse EDM. Figure 15(a) shows dual disk-type electrodes. Figure 15(b) shows dual micro columns, which were machined with dual disk-type electrodes.

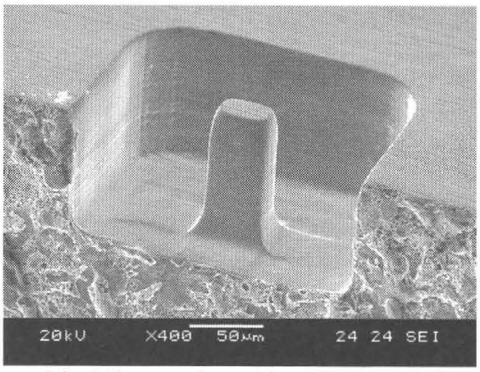
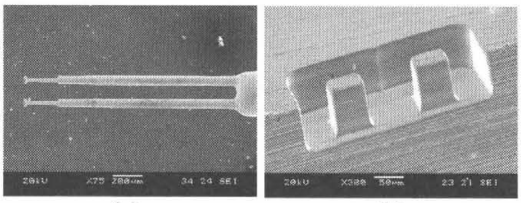


Figure 14. Micro column by disk-type electrode (304 SS, 40 µm width, 20 µm length, 85 µm height, 6 V, 60 ns pulse on-time, 1 µs period).

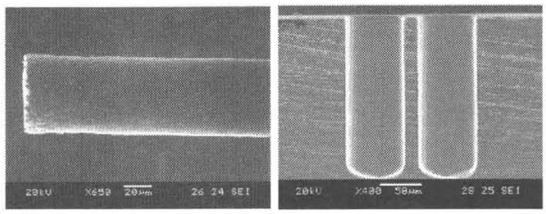


(a) (b)

Figure 15. (a) dual disk-type electrodes (WC, 45 µm disk diameter, 20 µm neck diameter), (b) dual columns machined with dual disk-type electrodes (304 SS, 58 µm width, 83 µm height, 6 V, 60 ns pulse on-time, 1 µs period).

6.2. Insulated tool

More recently, the method of using an insulated micro tool was reported to prevent side dissolution [11]. Enamel is resistive to most chemicals and is thus suitable as an insulation coating for micro ECM. One of the most important points in insulation coating is that the insulation thickness should be smaller than the machining gap. Therefore, the insulation layer should be a few micrometers thick. In the insulation method, a diluted enamel droplet is dropped over the tool electrode with its bottom surface facing upward. When the enamel coating dries up, the bottom surface is rubbed against a hard surface and is machined by EDM to remove the remaining enamel. Then, the bottom surface, which corresponds to the machining area, is disclosed. Figure 16(a) shows an example of an insulated tool electrode. The insulation thickness is about 3 µm more than the electrode of 800 µm in length. It takes only a few minutes to form an insulation layer. Figure 16(b) shows the cross sectional view of a micro wall, which was machined by the insulated tool electrode.



(a) (b)

Figure 16. (a) insulated tool electrode, (b) micro wall (cross sectional view, 304 SS, Ø 56 µm tool, 160 µm height, 15 µm width, 400 µm length, pulse: 6 V, 60 ns / 1 µs).

7. WIRE ELECTROCHEMICAL MACHINING

Wire electrochemical machining (Wire ECM) is another promising machining method. As shown in Figure 17, a micro wire is used as a tool electrode. In contrast to wire EDM, because the wire is not worn out in ECM, thinner wire can be used and wire feeding is not necessary. Wire ECM can be used as wire cutting for fabrication of micro parts. In this paper, by using platinum and tungsten wire with 10 µm diameter, various micro grooves were machined. Since the wire was very flexible, contact with the workpiece had to be avoided. Figure 18 and 19 show a micro groove and a micro gear, which were machined by wire ECM.

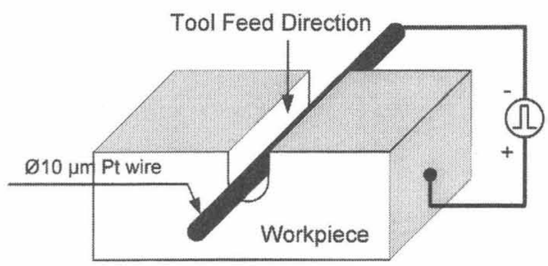


Figure 17. Schematic diagram of Wire ECM.

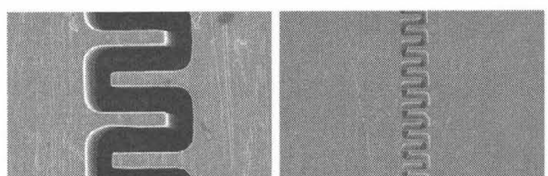


Figure 18. Micro groove shape on 304 stainless steel (Φ_{work} = 0.4 V_{Pt}, Φ_{tool} = 0 V_{Pt}, applied voltage: 6.5 V, pulse period: 7 µs, pulse on-time: 75 ns, electrolyte: 0.1 M H_2SO_4).

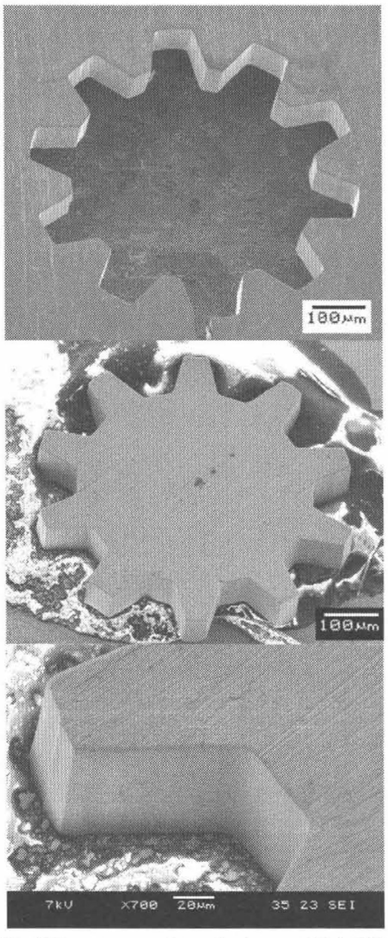
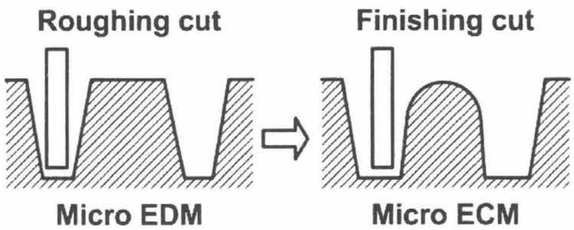


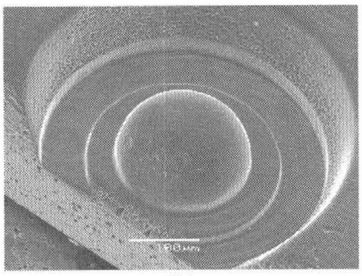
Figure 19. Micro gear (workpiece: 304 SS, Φ_{work} = 0.4 V_{Pt}, Φ_{tool} = 0 V_{Pt}, applied voltage: 6.5 V, pulse period: 7 μs, pulse on-time: 75 ns, electrolyte: 0.1 M H_2SO_4)

8. HYBRID MACHINING

Micro ECM can be applied without the compensation of tool wear. When using micro ECM on stainless steel, the surface quality is better than the results of using micro EDM. However, the tool feedrate in micro ECM is only a few μm/s, which is slower than that of micro EDM. The structure of micro ECM machine is similar to that of micro EDM, which also includes using a voltage source and a micro tool electrode. In both processes, a workpiece is placed in a bath, which is filled with electrolyte or dielectric fluid. Therefore, a hybrid machining process which uses both micro EDM and micro ECM can be considered [12]. As shown in Figure 20, micro EDM is used for a roughing cut and micro ECM is used for a finishing cut. The method can reduce machining time while increasing machining accuracy and surface quality. Since a water-based electrolyte is used in the ECM process which follows the EDM process, water that is highly resistive is preferred rather than kerosene in EDM.



(a)



(b)

Figure 20. (a) Schematic diagram of hybrid process, (b) micro hemisphere machined by EDM/ECM hybrid process (304 SS, 100 μm radius hemisphere, Ø 58 μm electrode)

9. CONCLUSION

State of the art technology has been presented in this paper by demonstrating ECM using ultra short pulses. ECM by using ultra short pulses is a promising technology. It can be used not only in micro machining, but also 3 dimensional nano machining without tool wear. Although the process is based on electrochemical dissolution like conventional ECM, the process of applying nanosecond pulses to electrochemistry has not been as well known. To improve accuracy, reliability and efficiency in the process, however, further investigation is needed.

10. REFERENCE

[1] Schuster, R., Kirchner, V., Allongue, P., Ertl, G., 2000, Electrochemical Micromachining, Science, Vol. 289, pp. 98-101.

[2] Kim, B. H., Ryu, S. H., Choi, D. K., Chu, C. N., 2005, Micro Electrochemical Milling, J. Micromech. Microeng., Vol. 15, No. 1, pp. 124-129.

[3] Kock, M., Kirchner, V., Schuster, R., 2003, Electrochemical Micromachining with Ultrashort Voltage Pulses - a Versatile Method with Lithographical Precision, Electrochim. Acta, Vol. 48, pp. 3213-3219.

[4] Bard, A. J., Faulkner, L. R., 2001, Electrochemical Methods, Fundamentals and Applications, John Wiley and Sons, New York.

[5] Kirchner, V., 2002, Electrochemical Microstructuring with Ultrashort Voltage Pulses, Ph.D thesis, Freie Universität Berlin.
[6] Masuzawa, T., Fujino, M., Kobayashi, K., 1985 Wire Electro-discharge Grinding Method, Annals of CIRP, Vol. 34, No. 1, pp. 431-434.
[7] Choi, S. H., Kim, B. H., Chu, C. N., 2006, Micro Electrochemical Machining of Tungsten Carbide (Korean), J. Korean Soc. Prec. Eng., Vol. 23, No. 12, pp. 111-116.
[8] Cagnon, L., Kirchner, V., Kock, M., Schuster, R., Ertl, G., Gmelin, W. T., Kück, H., 2003, Electrochemical Micromachining of Stainless Steel by Ultra Short Voltage Pulses, Z. Phys. Chem., Vol. 217, pp. 299-313.
[9] Allongue, P., Jiang, P., Kirchner, V., Trimmer, A. L., Schuster, R., 2004, Electrochemical Micromachining of p-Type Silicon, J. Phys. Chem., Vol. 108, pp. 14434-14439.
[10] Ahn, S. H., Ryu, S. H., Choi, D. K., Chu, C. N., 2004, Electrochemical Micro Drilling Using Ultra Short Pulses, Prec. Eng., Vol. 28, No. 2, pp. 129-134.
[11] Park, B. J., Kim, B. H., Chu, C. N., 2006, The Effects of Tool Electrode Size on Characteristics of Micro Electrochemical Machining, Annals of the CIRP, Vol. 55, No. 1, pp. 197-200.
[12] Jeon, D. H., Kim, B. H., Chu, C. N., 2006, Micro Machining by EDM and ECM (Korean), J. Kor. Soc. Prec. Eng., Vol. 23, No. 10, pp. 52-59.