Fabrication of High Aspect Ratio Cylindrical Tungsten Micro Tool by Reverse Micro-ECM Process

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Abstract

Micro tool fabrication is one of the most important aspects of the micromachining due its versatile use in generation of 1D, 2D and 3D features, which are used in parts in MEMS and micro devices. Electrochemical micro machining has shown huge potential to fabricate micro electrodes of high aspect ratio with better surface integrity and defect free surface. In reverse micro-ECM process the tool is first fabricated in situ in the machine by giving it the positive polarity. Once the tool is completely prepared it is given negative polarity so that normal ECM with the targeted job may be carried out. In this study pure tungsten micro electrode of high aspect ratio of 10 was fabricated in reverse micro ECM process. The experiments were conducted by taking a 1 mm diameter cylindrical tungsten rod as anode and three different types of cathodes namely, brass wire of 200 µm diameter, brass disc of 1 mm thickness and brass block of size (1×1×0.5) cm. The machining was carried out in KOH solution with varying process parameters like voltage, duty ratio, concentration of electrolyte and reciprocating feed of tungsten rod. By analyzing at different combination of parameters, microelectrodes of diameter below 20 µm could be obtained. A comparative study for micro electrodes, fabricated using different cathodes i.e. wire, disc and block, was presented by taking taper and surface integrity as the quality parameters.

Keywords: Micro electrochemical machining, Micro machining, Tungsten micro tool, High aspect ratio, Surface integrity, Tool geometry

1. INTRODUCTION

Micro machining has become an important aspect of modern industries due to the miniaturization of products with features of high resolution, that are in huge demand in electronics, photonics, aviation and biomedical industries. Micro tool is an important aspect of micro machining as it is used to fabricate different 1D, 2D and 3D micro features. Hence fabrication of micro tool is an important research area. In general micro electrodes should have the properties like high electrical and thermal conductivity, high erosion resistance and high stiffness. These features are commonly found in tungsten, which is fabricated to obtain cylindrical micro tool using processes like micro electro discharge machining (micro EDM), micro electro chemical machining (micro ECM), laser machining etc. Tungsten electrodes are used as tool electrodes in micro-EDM and micro-ECM. Out of the above processes, micro-ECM is gaining popularity for micro tool fabrication as it removes material by anodic dissolution process which produces surface with no residual stress [1] which is a disadvantage in thermal processes like EDM and laser machining. The fabrication of micro tools having diameter less than 100 µm is often difficult in conventional machining as it gets easily deformed due to the lateral force [2]. Electro chemical etching technique is also a popular method to fabricate micro tools of size less than 50 µm but it is difficult to control and it can only fabricate micro tools with rotational structure [3,4]. But micro-ECM process is a very good technique where the anodic dissolution can be controlled to achieve a high aspect ratio and better accuracy during micro tool fabrication. Reverse ECM is one of the earliest methods developed for micro tool fabrication, where the polarity of the tool and work piece is reversed and a sacrificial block is used as cathode [5, 6]. Once the tool is completely prepared, it is given negative polarity so that normal ECM with the targeted job may be carried out. Generally, KOH or NaOH electrolyte is used for anodic dissolution of tungsten in reverse micro-ECM process [7]. In KOH solution at the anode the metal tungsten gets oxidized into tungstate (WO_3) and disintegrates from the parent material by diffusion and migration. This process is facilitated by a DC power supply between the anode and the cathode. Fan et al. [8] used a pulsed dc power supply, where the need of pulse off time is greatly emphasized as it helps in reducing formation of diffusion layer around the tungsten. Due to the application of pulsed power supply, the debris removal becomes efficient as there is no material removal during pulse off time. The machining accuracy in micro meter range can also be achieved with the application of ultra short voltage pulses ranging from few nano seconds to few tens of nano second [9]. Wire ECM process similar to wire electro discharge grinding (WEDG) has evolved as a promising technique for micro tool fabrication as metal wire is inexpensive and flexible, in comparison to the sacrificial metal block used in reverse ECM process [10]. Zhu et al [11] developed an in situ wire electrode of diameter 5 µm for the production of many complex micro structures of several ten micro meters. Despite the fact that very small diameter of the order of tens of micro meter were achieved by the researchers in micro-EDM and micro-ECM process, high aspect ratio micro tool somehow could not be achieved in micro-ECM process.

In this study pure tungsten micro electrode of high aspect ratio of 10 was fabricated in reverse micro ECM process. The experiments were conducted by initially taking a 1 mm diameter cylindrical tungsten rod as anode and three different types of cathodes, namely, brass wire of 200 µm diameter, brass disc of 1 mm thickness and brass block of size (1×1×0.5) cm. The machining was done in KOH solution with different process parameters like voltage, duty ratio, concentration of electrolyte and reciprocating feed of the tungsten rod. By experimenting at different combination of parameters microelectrodes of diameter below 20 µm could be obtained. A comparative study for micro electrodes fabricated using different cathodes, i.e. wire, disc and block, was presented by taking taper and surface integrity as the quality parameters.

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2. MATERIALS AND METHODS

2.1 Materials

Tungsten is considered as a favorable material for micro tool due to its specific characteristics, for example, like good electrical conductivity, thermal conductivity, and corrosion resistance. In the present study pure Tungsten of 1 mm diameter was used for micro tool fabrication. The chemical composition of the tungsten is given in the table 1. Zinc is alloyed to copper to produce brass wire, which is the most common EDM wire in use today. Zinc has a lower melting/vaporization point, which makes it a better electrode material than copper. In this case of processing tungsten by micro-ECM, the anode surface tends to generate a thin oxidized layer when applying neutral electrolytic solutions, for example, NaCl and $NaNO_3$. This oxidized layer is insoluble within neutral electrolyte environment and prevents the anode participating electro chemical reaction. However, the oxidized layer could be removed by alkaline solution. As a result, KOH is selected as working electrolyte for this experiment.

Table 1: Chemical composition of the Tungsten tool

Element	K	C	O	W
Wt. %	0.01	0.01	0.03	99.95

2.2 Methods

In this study, all machining experiments were conducted in the commercially available TTECM-10 set up of ECM process. The ECMM arrangement consisted of pulse power supply, computer, machining chamber, electrolyte circulation system, filtration unit, reservoir and pump. The schematic arrangement of the machine unit is given in figure 1. The maximum travel range for bed was limited to 135 mm(X) × 60 mm(Y) × 70 mm (Z) with minimum resolution of 1 µm. The whole arrangement of ECM was integrated with and governed by high-performance computer with the help of Hyper 2GUI software. In this investigation applied voltage, duty ratio, electrolyte concentration, tool rpm, reciprocating feed were taken as process parameters. The tool was fabricated by two processes i.e. rough machining and fine machining. In rough machining a high voltage of 20 V and high concentration KOH of 0.4 M was used to remove material quickly and then fine machining was done with 10 V voltage and 0.05 M concentration. The values of all process parameters are given in the table 2.

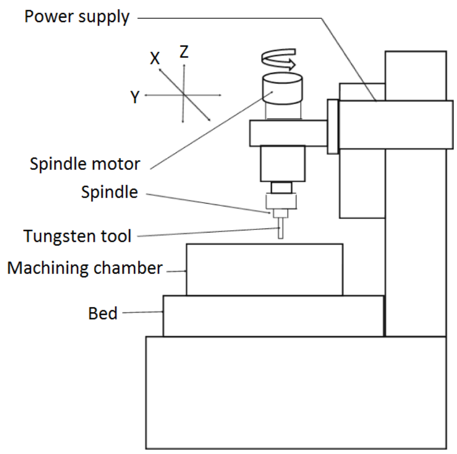

Fig. 1. Schematic layout of ECM set up

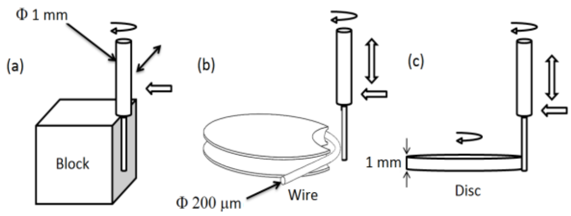

Fig. 2. Sacrificial electrodes (a) block, (b) running wire, and (c) rotating disc

Table 2: Experimental conditions for reverse micro-ECM

S. No	Process name	Process parameters					Initial dia (µm)	Final average dia (D) (µm)	Length (L) (mm)	Aspect ratio (L/D)	Taper (degree)
		Voltage (V)	Duty ratio (%)	Conc. of KOH (M)	Tool RPM	Reciprocating feed (µm/s)					
1	Wire micro ECM (200 µm wire)					100		103.0	1.239	12.02	Irregular surface
2						100		114.3	1.057	9.24	Irregular surface
3	Disc micro ECM 1 mm disc	10 20	50	0.05 0.4	2000	100	1000	159.7	1.480	9.26	3.37
4						100		122.0	2.271	18.61	2.58
5	Block micro ECM (1×1×0.5) cm					No reciprocating motion		221.3	1.974	8.9	Irregular surface
6						No reciprocating motion		16.82	0.317	18.84	3.3

3. RESULTS AND DISCUSSIONS

In the present study of the tool–electrode fabrication process, three different sacrificial electrodes were tested to compare their capability and performance. Fig. 2 shows the three different types of sacrificial electrodes. Fig. 2(a) shows a stationary block, which is the simplest method to machine a tool–electrode. Fig. 2(b) shows a guided running wire as a sacrificial electrode of 0.2 mm in diameter. The wire running speed is about 0.2–1 mm/s. This method is known as wire electro chemical machining, and it is a typical method for micro-ECM. Fig. 2(c) shows a rotating electrode with 1 mm in thickness and 150 mm in diameter. The rotating speed of the disc electrode was about 2 rpm during tool fabrication. During the tool fabrication process, the spindle was rotating about 2000 rpm and it was made to move up and down with a reciprocating feed of 100 µm/sec. This means that the spindle was under control to maintain the inter-electrode gap. Once the tool reached one end of its stroke movement, the tool moved toward the electrode to a given depth of cut, and the process was repeated. For block ECM process reciprocating motion was not given, as the block thickness was more as compared to wire and disc, the lower side of the micro tool always remained in close proximity with the block increasing the anodic dissolution from that region. To avoid this problem, side wise movement to the tool against the block was given to facilitate the equal metal removal from the entire region. Two sets of experiments were conducted for each sacrificial electrode to access the repeatability of each process.

3.1 Effects of sacrificial electrode on the tool–electrode fabrication

Figures 3, 4 and 5 show SEM images of micro electrodes that were fabricated using reverse micro-ECM technique with different types of sacrificial electrodes. Fig. 3 shows the tool-electrode machined using a stationary brass block. At the time of tool fabrication, the job was rotated around its own axis and gradually fed towards the block electrode to maintain the uniform inter-electrode gap. The diameter of the cylindrical rod gradually reduces at uniform rate when a required voltage is applied between the electrodes [6]. Initially the surface of the fabricated tool–electrode was generally smooth. However, the shape accuracy was not as good as desired, and the tool usually had some taper. Since the tool moved sideways along the surface of the block, the anodic dissolution took place as long as a potential difference continued to be applied. Therefore, it can be seen from the experimental table that a taper angle about 3.3 degrees is obtained. Slight tilting of the electrode block toward the tool–electrode did not help to improve the tapered shape. The electrode still had uneven diameter as shown in Fig. 3. The stationary sacrificial block electrode was easy to install; however, the shape and dimensions were not easy to control.

Figure 2(b) shows the principle of micro tool fabrication using reverse wire ECM. The tungsten rod, which was able to be moved reciprocally in z-direction and rotationally about the z-axis, was connected to the positive pole of the power source. The brass wire with diameter 200 µm was employed as cathode and connected with negative pole of the power source. The brass wire could be fed linearly along the x-axis and perpendicular to the z-axis. Hence, due to the coupling of linear motion of wire electrode on x-axis, linear motion and rotation of workpiece on z-axis the proposed process was able to produce micro tool [10]. Fig. 4 is a typical surface condition of the tool–electrode, which is machined by ECM using a running wire. Since a fresh wire was continuously used, the dimensional change of the sacrificial electrode was theoretically zero. This fact ensured high-accuracy dimensional control in micro-ECM. However, the surface finishing efficiency was not as high as that of the rotating disk electrode method. This was due to the fact that the diameter of the running wire was only 0.2 mm and it was not enough to finish the machined surface smoothly using the same condition of ECM gap control used for rotating disc electrode. Although an irregular surface was obtained, an aspect ratio of 12.02 was possible to be achieved. To achieve a better surface using this thin wire, the speed of the finishing process must be reduced. In figure 4, at base of the micro tool, the neck formation could be observed. This phenomenon occurs due to the high current density at the interface between air and KOH electrolyte. The diffusion layer, which arises due to the accumulation of ions near the tungsten rod, is the highest at the tip and gradually decreases upwards. The H_2 gas formed rises above and bursts while reaching at the interface of air and electrolyte. The energy released from bursting breaks the diffusion layer at the interface between air and electrolyte, thus, more dissolution takes place as current can easily pass through a thin or no diffusion layer at the shank portion, giving rise to a neck [12].

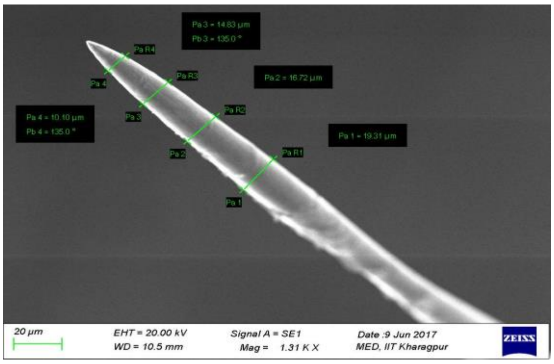

Fig. 3. Electrode obtained by using sacrificial block

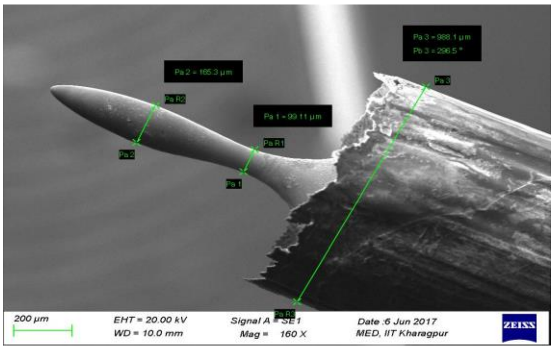

Fig.4. Electrode obtained by using running wire

Fig. 5 shows an example of tool–electrode fabrication using a rotating sacrificial disc electrode. Taking into consideration of the diameter difference between the tool–electrode and sacrificial disc electrode, the dimensional change of the rotating disc electrode was almost negligible in the tool–electrode fabrication using micro-ECM. The 1 mm thickness of the rotating electrode resulted in the same effect as stationary electrode on the surface finish, since it was wide enough to finish a smooth surface. In comparison to running wire electrode, disc electrode may be producing uniform current flux during anodic dissolution process as illustrated in figure 6.

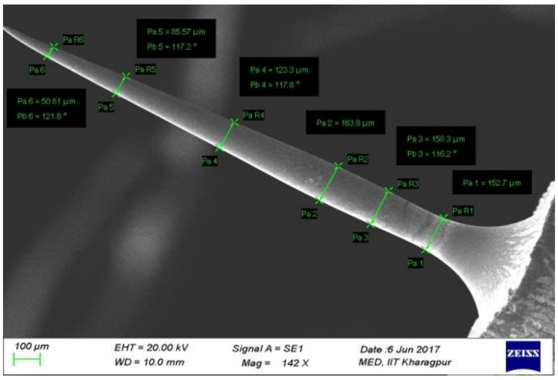

Fig. 5. Electrode obtained by using rotating disc

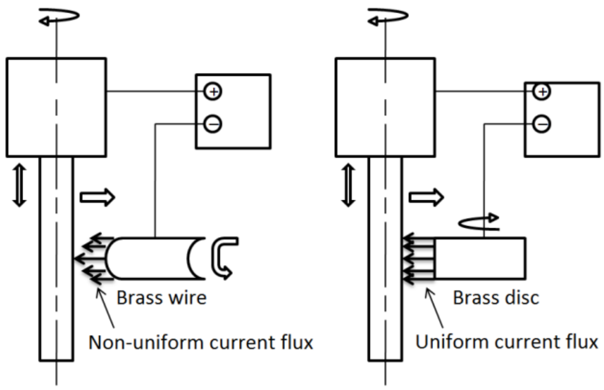

Fig. 6. Current flux variations in wire-ECM and disc-ECM

As the disc has sharp and flat edges, the current flux is uniform in inter electrode gap (IEG), which contributes to better quality product in comparison to wire electrode. But in a running wire case, due to curvilinear shape of wire, the current flux is not uniform in the IEG which may cause uneven material removal from the tungsten rod [13]. In the current study a high aspect ratio of 18.61 was achieved but there remained a taper of 2.58 degree, which was less in comparison to the other two methods. From the comparison of the three different methods, the rotating disc electrode method was 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 system followed by compensation-machining.

4. CONCLUSION

In this study, an attempt was made to fabricate a high-aspect ratio micro-tool using reverse micro-ECM. Three different types of sacrificial electrodes were tested to assess their performance for tool–electrode fabrication. The rotating disc electrode showed the best performance in the high-aspect ratio tool–electrode fabrication with an aspect ratio of 18.61.

References

[1] Bhattacharyya, B., & Munda, J., Experimental investigation on the influence of electrochemical machining parameters on machining rate and accuracy in micromachining domain. *International Journal of Machine Tools and Manufacture*, *43*(13), 1301-1310, 2003.

[2] Yamagata, Y., & Higuchi, T., Three-dimensional micro fabrication by precision cutting technique. *JOURNAL-JAPAN SOCIETY FOR PRECISION ENGINEERING*, *61*, 1361-1364, 1995.

[3] Lim, Y. M., & Kim, S. H., An electrochemical fabrication method for extremely thin cylindrical micropin. *International Journal of Machine Tools and Manufacture*, *41*(15), 2287-2296. 2001.

[4] Wang, Y., Zeng, Y., Qu, N., & Zhu, D., Fabrication of sub-micro spherical probes by liquid membrane pulsed electrochemical etching. *Journal of Materials Processing Technology*, *231*, 171-178, 2016.

[5] Das, A. K., & Saha, P., Analysis on fabrication of micro-tools by micro-electrochemical machining process. *International Journal of Nanomanufacturing*, *9*(1), 66-76, 2013.

[6] Das, A. K., & Saha, P., Fabrication of cylindrical micro tools by micro electrochemical form turning operation. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *228*(1), 74-81, 2014.

[7] Bhattacharyya, B. , *Electrochemical micromachining for nanofabrication, MEMS and nanotechnology*. William Andrew, 2015.

[8] Fan, Z. W., Hourng, L. W., & Wang, C. Y., Fabrication of tungsten microelectrodes using pulsed electrochemical machining. *Precision Engineering*, *34*(3), 489-496, 2010.

[9] Kock, M., Kirchner, V., & Schuster, R., Electrochemical micromachining with ultrashort voltage pulses–a versatile method with lithographical precision. *Electrochimica Acta*, *48*(20), 3213-3219, 2003.

[10] Liu, Z., Zeng, Y., & Zhang, W.,Fabrication of metal microtool applying wire electrochemical machining. *Advances in Mechanical Engineering*, *6*, 382105, 2014.

[11] Zhu, D., Wang, K., & Qu, N. S., Micro wire electrochemical cutting by using in situ fabricated wire electrode. *CIRP Annals-Manufacturing Technology*, *56*(1), 241-244, 2007.

[12] Ghoshal, B., & Bhattacharyya, B. Influence of vibration on micro-tool fabrication by electrochemical machining. *International Journal of Machine Tools and Manufacture*, *64*, 49-59, 2013.

[13] Jo, C. H., Kim, B. H., & Chu, C. N.,Micro electrochemical machining for complex internal micro features. *CIRP Annals-Manufacturing Technology*, *58*(1), 181-184, 2009.