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FABRICATION OF HIGH-ASPECT-RATIO EDM MICROELECTRODES USING ON-THE-MACHINE TOOL FABRICATION TECHNIQUES

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ABSTRACT

The concept of fabricating on-machine high-aspect-ratio microelectrodes arise from the need of machining small and deep micro-holes in micro-electro-discharge machining (micro-EDM). In recent years, the need for fabricating microelectrodes has gained much importance owing to the wide industrial applicability of micro-EDM technology for precise micro-hole fabrication and micro mold making. Therefore, present study aims to investigate the feasibility of fabricating high-aspect-ratio microelectrodes using block-µEDM and turning-µEDM processes. The process description and important aspects in fabricating successful, small diameter and high-aspect-ratio microelectrodes have been presented. Finally, a comparative study on the capabilities of the two processes and the application of fabricated microelectrodes in deep-hole micro-EDM drilling of WC has been presented.

Keywords: High-aspect-ratio Microelectrodes, On-the-machine Tool Fabrication, Turning-µEDM Hybrid Process, Block-µEDM Process, Micro-EDM Drilling, Tungsten Carbide.

1. INTRODUCTION

Electrical discharge machining, more commonly known as EDM or spark machining, removes electrically conductive material by means of rapid, repetitive spark discharges from electric pulse generators with the dielectric flowing between the tool and the workpiece. Micro-electrodischarge machining (Micro-EDM) is the application of EDM in micro field. The low energy range is becoming important when the EDM process is used in micro field. Micro-EDM has similar characteristics as EDM except that the size of the tool, discharge energy and movement resolutions are at micron level.

In recent years, the need for fabricating microelectrodes has gained much importance owing to the wide industrial applicability of micro-EDM technology for precise micro-hole fabrication and micro mold making [1-3]. Several researches have been carried out on the on-machine fabrication of microelectrodes. A number of EDM based processes for fabricating microelectrodes have been reported; such as wire electro-discharge grinding (WEDG), mesh electrode method and block electrode method [4]. With the development of WEDG technology, micro-EDM has become the machining process of choice for fabricating micro/miniature parts [5]. However, the process requires design and installment of WEDG device on the machine, which needs investments and special design consideration. Multiple electrodes have been fabricated successfully using reverse EDM for different application like punching of arrays of micro-holes, ECM etc. [6]. In addition, mesh electrode method of fabricating multiple electrodes has also been reported [7]. However, the reverse EDM process is very time consuming and it is very difficult to fabricate very high-aspect-ratio micro-electrodes using reverse EDM. Similarly, machining down to a few tens of microns using mesh electrode method may be exigent due to the difficulty of flushing the debris from the micro tool electrode consisting of a micro-hole [4]. Besides, micro-EDM based processes; there are processes for fabricating microelectrodes, like LIGA [8-9] and micromechanical machining method [10-11]. However, the LIGA process requires very expensive and special facilities, and the maximum achievable thickness is relatively small.

Among all the microelectrode fabrication processes, the use of a conductive block as a cutting electrode and the rod as a workpiece of the block electrode method has been identified as being a simple and useful approach for producing microelectrodes due to its low investment cost and quick set-up [4,12]. However, there are several problems of block-EDM process like maintaining desired diameter and taperness of the fabricated microelectrodes due to occurrence of the wear in both electrode and the block [4]. Therefore, it requires further investigation for improving the performance. Moreover, in recent years, a new technology, turning-EDM hybrid machining technology has been reported to be a successful process for fabrication of microelectrodes

[13]. However, a number of issues remain to be solved for successful fabrication of microelectrodes with high-aspect-ratio and improved dimensional accuracy.

Therefore, investigations have been conducted for fabricating high-aspect-ratio microelectrodes using block-μEDM and turning-μEDM processes and to apply the microelectrodes in deep-hole micro-EDM drilling of difficult-to-machine tungsten carbide (WC).

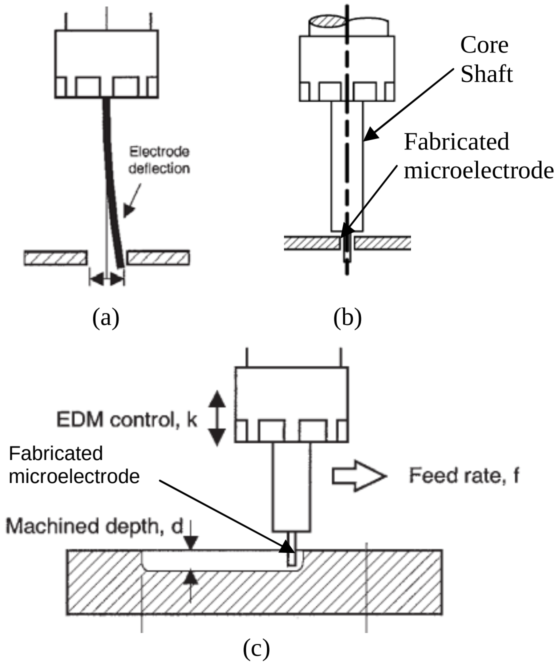


Fig 1. (a) Machining with longer electrodes introduces deflection due to low stiffness, (b) Micro-EDM drilling with on-machine fabricated microelectrode, (c) micromold fabrication using on-machine fabricated microelectrode.

2. PROBLEM STATEMENT

With the growing trends towards the miniaturization of machined parts and developments in the area of micro-electromechanical systems (MEMS), fabrication of micromold cavities has become the most important part for mass production of microcomponents. The microcomponents can be made easily using the injection molding process. However, hard-to-machine work piece materials should be machined very precisely in three-dimensional forms over the range of microns for the purpose of microinjection. In recent years, micro--EDM has become one of the alternative machining processes that can be used successfully for the fabrication of complex three-dimensional molds using very tough die materials. Micro-EDM can machine almost every conductive material, regardless of its stiffness. Using a very thin electrode and controlling the EDM contour, micromolds can be produced successfully.

Although micro-EDM plays an important role in the field of micromolds, it has disadvantages, including a high electrode wear ratio and a low material removal rate. The wear of the electrode must be compensated either by changing the electrode or by preparing the longer electrode from the beginning or fabricating the electrode in situ for further machining. Changing the microelectrode during machining is not recommended, because it may reduce the accuracy due to clamping. However, machining longer electrodes introduces deflection due to low stiffness, as illustrated in Fig. 1.

Moreover, in the micro-EDM process, the electrodes used are in micron level and their handling becomes difficult, as there is huge chance of bending the electrode during putting it into the collets. Therefore, it is more desirable that microelectrodes should be fabricated on-machine and will be used in micro-EDM directly without changing the tool; so that clamping and run out error could be minimized as well as machining accuracy can be improved.

3. EXPERIMENTAL SETUP

3.1 Machine tool

A multi-purpose miniature machine tool, developed for high-precision micro-machining at the National University of Singapore, was used for both on-machine fabrication of microelectrodes and micro-EDM drilling. The machine is capable of micro-EDM, micro-turning, micro-milling, micro-grinding, and micro-ECM by using suitable attachments. The maximum travel range of the machine is 210 mm (x-direction) × 110 mm (y-direction) × 110 mm (z-direction) with a resolution of 0.1 μm in all three directions. A full closed-loop-feedback control system ensures sub-micron accuracy. Fig. 2 shows the schematic diagram of the setup with multipurpose miniature machine tool.

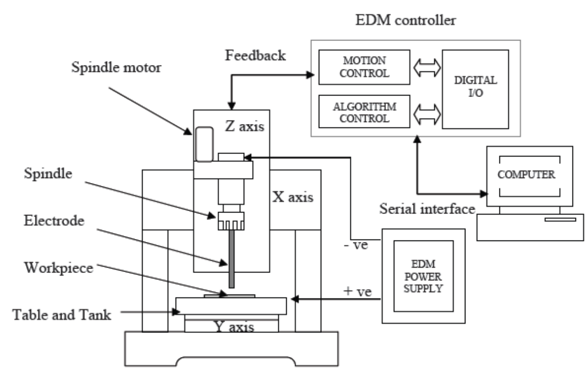


Fig 2. Schematic diagram of the setup with multi-purpose miniature machine tool.

3.2 Materials for Turning-μEDM process

For fabrication of microelectrodes using Turning-μEDM hybrid process, commercially available brass and CuW shafts of 6 mm diameter was used as workpiece. The cutting tool used were commercially available SumiDIA PCD positive rake insert type TCMD73X (0.1 mm nose radius, 7^{o} front clearance and 10^{o} rake angle). The tool shank used was Sumitomo type STGCR1010-09.

3.3 Materials for Block-μEDM process

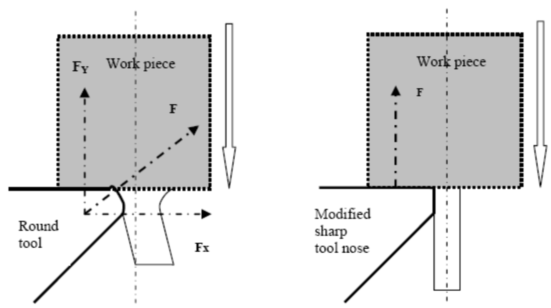
For fabrication of microelectrodes using Block-μEDM process, commercially available W and CuW (40% Cu, 60% W) of 0.5 mm diameter was used as workpiece and a carbide block with composition

WC-10wt%Co was used as sacrificial block. For the on-machine micro-EDM drilling, WC-10wt%Co workpiece of different thickness (0.1, 0.3, 0.5 and 1 mm) was used.

4. TURNING-μEDM HYBRID PROCESS

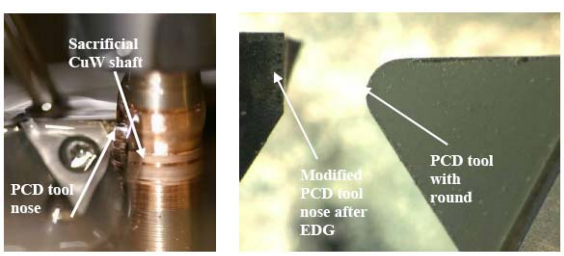
4.1 Modification of PCD cutting tool using micro-EDG process

Commercially available PCD tools usually have relatively large tool nose designed for general-purpose machining. The tool nose resolves the cutting force into two main components with one of them generating the essential cutting motion (F_y) while the other one producing radial force (F_x) causing deflection to the micro-shaft [Fig. 3(a)]. Hence, in order to fabricate straight shaft at small diameter, commercial PCD tool nose is modified to reduce the nose radius thus minimizing the force component (F_x), that causes the shaft deflection during microturning.



(a) (b)

Fig 3. (a) Resolution of cutting forces for microturning with a radius tool nose of commercial PCD insert, (b) Modified sharp tool nose to reduce F_X component.



(a) (b)

Fig 4. (a) On-machine EDG on PCD cutter, (b) PCD cutter before and after modification using EDG.

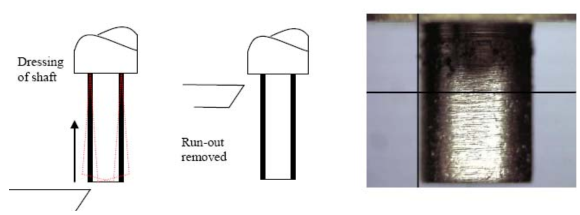
Micro-Electro-discharge grinding (EDG) is carried out by first setting the polarity of sacrificial copper tungsten (CuW) shaft to be negative and the PCD cutter to be modified as positive. A visual centering and pre-experimental dressing of the sacrificial CuW electrode has been done to ensure that any surface irregularity of the shaft is eliminated. The EDG of the PCD cutter was conducted using slow feed rate of sacrificial electrode towards the cutter nose and using different scanning motion to ensure precise sharpening and good surface finish of the nose and to avoid any possible formation of circular contours on the PCD cutter's surface mapped from the electrode's circular geometry. Figs. 4(a) and (b) present the on-machine photographs of the EDG process and the PCD tool before and after modification. The experimental settings for the modification of PCD tool using micro-EDG are listed in Table 1.

Table 1: Parameters used for electrical discharge grinding (EDG) of PCD tool nose

Machining parameters	Rough Cut		Final Cut	
Gap voltage	120 V	High MRR	80 V	Fine surface finish
Capacitor	470 pF		100 pF	
Feed rate	20-25 μm/min		10 μm/min	
Spindle speed	1200 rpm		1200 rpm	
Electrode advance in X-axis	140 μm		10 μm	

4.2 Centering process

The centering process is the most important step for fabricating accurate and high-aspect-ratio microelectrodes. Without proper centering, the micro-shaft becomes tapered and can break at any point of machining, especially when a micro-shaft of less than 100 μm is attempted. Another important thing before centering is the reduction of wobbling effect for the initial electrode. With the help of a superimposed cross-hair as the datum under the on-machine microscope, the degree of run-out can be observed and thus reduced. Fig. 5 presents the schematic diagram and photograph of the approach taken in this study to remove the wobbling effect of the shaft. The centering is done for both the round and sharp edged PCD cutter mounted in two different positions.



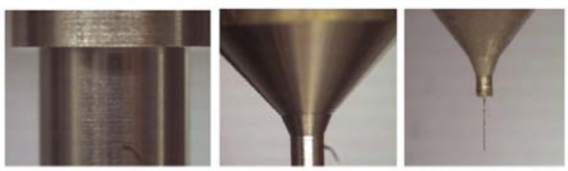
(a) (b) (c)

Fig 5. (a) Schematic representation of dressing in X and Z-axis to reduce wobbling effect, (b) removed wobbling (b) Cross-hair check before centering.

4.3 Microturning

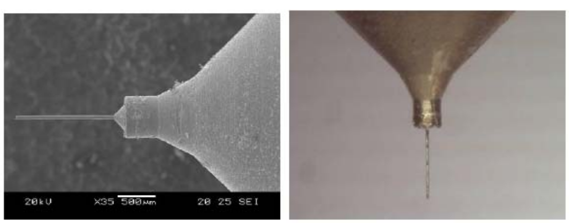
In this study, for the fabrication of high-aspect-ratio microelectrodes, three steps were used: straight microturning, taper microturning like pencil sharpener cutting, and final cutting using the modified PCD tool. In the first approach of straight turning, a small depth is dressed in order to reduce the wobbling effect of the initial shaft. The amount of materials removal using this straight turning was kept lower in order to avoid the stress concentration effect at the critical places of varying diameter. Before final cut, another necessary step is to carve out a tapered surface called the pencil sharpener to provide a strong support to the shaft with smooth gradient. The tapered surface is generated by gradual removal material turning along the taper surface by a limited depth of cut to protect the cutting edge from chipping. There are two reasons for choosing the taper turning process along the taper surface. Firstly, there is a chance of remaining the cutting marks on the surface in case of stepped taper turning parallel to the axis, which can act as the point of stress concentration. Secondly, from the view point of efficient and fast micro fabrication, turning parallel to the taper surface is preferable than that of parallel to the workpiece axis [14].

The final fabrication of the micro-shaft is done in a single pass at the tapered tip, reducing the diameter to the intended diameter. The purpose of creating the tip prior to the final cut is to allow a shallow depth of cut that prevents possible chipping of the cutter as well as to reduce the amount of debris that might interfere with the final turning process. Fig. 6 shows the on-machine images obtained during turning showing different steps of microturning at machining conditions listed in Table 2. Figs. 7(a) and (b) show the images of a fabricated 45 μm CuW shaft and 19.3 μm brass shafts respectively.



(a) (b) (c)

Fig 6. On-machine images of the shaft at different state of micro-turning (a) straight turning, (b) taper turning and (c) final shaft.



(a) (b)

Fig 7. (a) CuW microshaft of about 45 μm diameter, (b) brass shaft of 19.3μm diameter fabricated by Turning-μEDM hybrid process

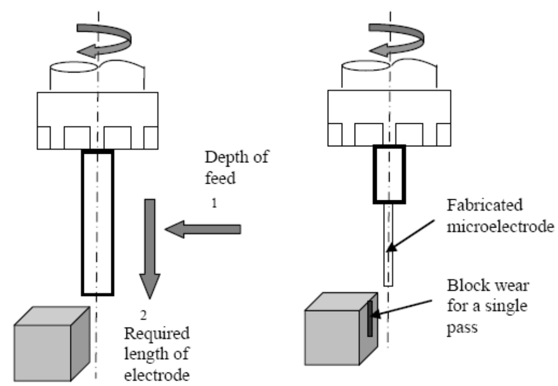
Table 2: Microturning with minimized tool wear

Material	Feed rate using round nose (mm/min)	Feed rate using modified nose (mm/min)	Depth of cut (mm)
CuW	1 - 40	1 - 5	Roughing: 0.2-0.3 Finishing: 0.05-0.1
Brass	1 - 100	1 - 40	Roughing: 0.3-0.7 Finishing: 0.1-0.3

5. BLOCK-μEDM PROCESS

5.1 Stationary Block-μEDM process

Block-μEDM is a simple process requiring very little arrangement in the setup. Fig. 8 shows the schematic diagram of the Block-μEDM process. It needs a precise sacrificial rectangular block with high wear resistance (WC was used in this study due to its high resistance to wear), and a commercially available electrode. However, one important thing is the alignment of block respective to the electrode. It is very important that sacrificial block should be aligned properly (within an accuracy of ±2 μm) in order to avoid electrodes being more taper, thus reducing dimensional accuracy. It has been found that due to wear of the sacrificial block also, the diameter of the fabricated electrode is sometimes difficult to predict. Therefore, an on-machine camera with measuring unit is installed in the setup to measure on-machine. In this method, the block is used as a cutting electrode and a cylindrical rod is used as the workpiece in the EDM process. The microelectrode that needs to be machined is fed against the conductive block. The machining is carried out at different conditions [shown in table 3] by applying a controlled electric spark and by forcing the dielectric medium to flow through the spark gap between the block and the rod.

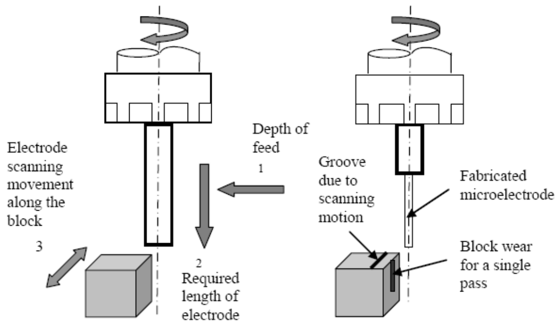


(a) (b)

Fig 8. Schematic diagram of Block-μEDM process; (a) at the beginning of process; (b) fabricated microelectrode

5.2 Moving-electrode Block-μEDM process

Although, the process is simple in mechanism, it needs several important considerations to fabricate successful, dimensionally accurate and very high aspect ratio microelectrodes. The major problem of block-μEDM is the taperness of the fabricated microelectrodes. Therefore, a new and modified block-μEDM process was developed using the scanning movement of the electrode in addition to downward movement. The introduction of scanning motion significantly reduces the taperness of the microelectrodes. The reason for taperness in stationary block is because, at the start of machining more surface area are exposed to spark zone, which decreases with the block wear. However, if the electrode is moved along the block, then the wear of the block is uniformly distributed which reduces the taperness of the microelectrodes. Fig. 9 shows Block-μEDM process with moving electrode.

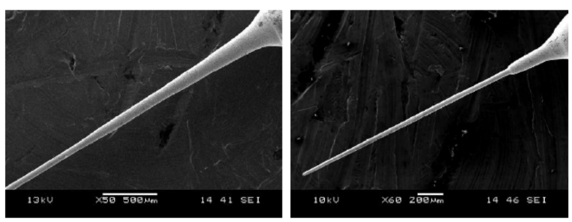


(a) (b)

Fig 9. Schematic diagram representing the Block-µEDM process with moving electrode; (a) at the beginning of process; (b) fabricated microelectrode

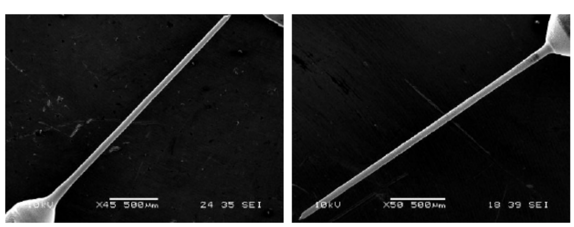
Table 3: Machining conditions for the fabrication of microelectrode using Block-µEDM

Electrode materials	CuW, W
Block material	WC-10wt%Co
Dielectric material	TOTAL FINA ELF EDM oil 3
Polarity	Electrode : +ve
Spindle speed	1500
Gap voltage (V)	80, 90, 100, 110, 120,
Capacitance (pF)	47, 100, 470, 1000, 2200, 4700
Feed length (µm)	12.5, 25, 50, 75, 100



(a) (b)

Fig 10. CuW microelectrode; (a) Ø 50 µm, L 3 mm (a.r. 60) fabricated by stationary Block-µEDM process, (b) Ø 40 µm, L 2 mm (a.r. 50) fabricated by Block-µEDM process with moving electrode [steps: see table 4].



(a) (b)

Fig 11. W microelectrode; (a) Ø 60 µm, L 3 mm (a.r. 50) fabricated by stationary Block-µEDM process, (b) Ø 40 µm, L 3 mm (a.r. 75) fabricated by Block-µEDM process with moving electrode.

Fig. 10(a) shows the fabricated CuW electrode of about 50 µm diameters and 3 mm long (a.r. 60) obtained using stationary Block-µEDM. The improvement in taperness can be observed from Fig. 10(b) where the microelectrode presented has been fabricated using Block-µEDM process with electrode movement. Figs. 11(a) and (b) show the fabricated W electrode using stationary and moving block-µEDM process. It has been observed that, moving block-µEDM process can provide microelectrodes with less taperness, thus providing better dimensional accuracy.

Table 4: Machining steps for fabricating a CuW microelectrode of Ø 40 µm, L 3 mm (Fig. 10b)

Machining step	Voltage (V)	Capacitance (pF)	Feed length (mm)	Average Machining Time (h:mm)
1	120	4700	0.050	0:13
2	120	4700	0.050	0:13
3	120	2200	0.050	0:18
4	120	2200	0.025	0:20
5	100	470	0.025	0:25
6	100	100	0.025	0:30
7	80	47	0.013	0:37
		Total average machining time		2:40

6. COMPARISON OF TWO PROCESSES

A comparative evaluation on the capabilities and performance of the two processes is listed in Table 5.

Table 5: Comparative evaluation of Turning-µEDM and Block-µEDM processes for microelectrode fabrication

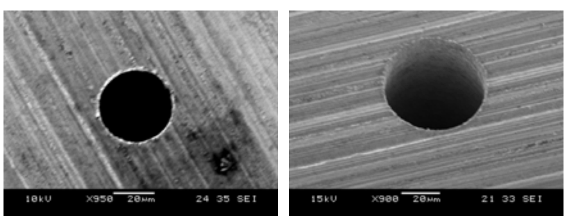
Factors of comparison	**Turning-µEDM hybrid process**	**Block-µEDM process**
Applicable Materials	Softer and easily machinable materials; e.g. Brass Difficult to apply in hard materials	Difficult-to-cut and soft/easily machinable materials with good electrical conductivity; Brass, CuW, W
Average fabrication time	Depends mainly on centering time PCD cutting tool modification: 10 mins Centering process: 15-30 mins Microturning process: 10 mins Total fabrication time: 30-45 min	Depends on the discharge energy used and number of machining passes For 4 passes of rouging and 3 passes of finishing: Total fabrication time: 2.5 hours
Dimensions	Brass: Ø 20 µm, L < 1 mm CuW: Ø 45 µm, L < 800 µm	CuW: Ø 45 µm, L: > 3 mm W: Ø 45 µm, L: > 3 mm
Aspect ratio	Brass: 45-55 CuW: 15-20	CuW: >70 W: >75
Taperness	Less taper	Comparatively more taper
Distortion	Suffer distortion	No distortion

Surface finish	Depends mainly on microturning conditions; e.g. feed rate and depth of cut R_a: < 1 µm (optical)	Depends mainly on energy used in finishing steps R_a: 0.5-1.5 µm (optical)

7. APPLICATION OF MICROELECTRODES

During the micro-EDM, for fabricating small and high-aspect-ratio micro-holes it requires several times higher electrode length than the thickness of the workpiece. It has been found that, the wear of the brass microelectrodes are very high compared to W and CuW microelectrodes during machining WC. This may be due to the reason that, the melting point of brass is much lower compared to that of WC. Therefore, to remove same unit of material from WC, more materials are removed from the brass. It was observed that electrodes obtained using turning-µEDM process is of limited height thus, are not capable of fabricating deeper micro-holes in WC. Fig. 12(a) shows a 30 µm hole in a WC strip of 0.1 mm machined by an Ø: 20 µm, L: 1 mm microelectrode fabricated using Turning-µEDM process.

On the other hand, for fabricating deep micro-holes, microelectrodes fabricated using block-µEDM process can perform well. As there is no force in this process, micro-electrodes of more than 3 mm in length 40 µm diameters can be used for deep-hole drilling in difficult-to-cut WC. Fig. 12(b) shows a micro-hole of 50 µm diameter in 0.5 mm WC sheet by a microelectrode (Ø: 45 µm, L: 3 mm) fabricated using Block-µEDM.



(a) (b)

Fig. 12: SEM images of micro-holes machined at 100 V, 100 pF; (a) Microelectrode: Turning-µEDM hybrid process; Micro-hole: Ø 30 µm hole in 0.1 mm WC strip, (a.r. 3.33); (b) Microelectrode: Block-µEDM process, Micro-hole: Ø 50 µm hole in 0.5 mm WC sheet, (a.r: 10).

8. CONCLUSIONS

The following conclusions can be drawn from this experimental study of on-machine fabrication of microelectrodes for micro-EDM application:

- Turning-µEDM is more suitable for fabricating smaller micro-holes with lower aspect ratios. This study shows that micro-electrodes of diameter down to 20 µm can be machined by this method.
- For fabricating deep micro-holes, micro-electrodes can be fabricated using block-µEDM process. As there is no force in this process, micro-electrodes can be fabricated more than 3 mm in length with less than 40 µm diameters.
- A newer process, Block-µEDM with scanning movement of the electrode can reduce the taperness significantly; thus reduce the shortcoming of stationary Block- µEDM process.
- Very small and high-aspect-ratio micro-holes in difficult-to-cut materials can be machined using micro-EDM drilling by means of the on-machine fabricated microelectrodes.

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