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Parametric Study for micro cutting tool fabrication by EDM process

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Abstract

Conventional micromachining process often faces the issue of unavailability of micro cutting tools of the desired dimensions. Many tool fabrication methods are inefficient for fabricating micro cutting tools less than 100 um. Micro Electro discharge machining (EDM) is a promising alternative for these tool fabrication methods because of its force free nature during machining. A four flute end mill tool fabricated using die sinking EDM is used to prove the feasibility of using EDM'ed tools for fabrication of microchannels. However, to get a stringent control over the tool dimensions, the relationships between the process parameters and final tool dimensions have to be well studied. In this paper, an experimental study with different parametric settings is done to understand the process and to find out the optimum parameters for higher dimensional accuracy and surface quality of the micro tool. Reduction in machined depth due to tool erosion and overcut due to side sparking will introduce inaccuracies in tool geometry during fabrication of micro tool. Analysis of variance (ANOVA) tool is used to recognize the relationship of EDM parameters with inaccuracies in tool geometry as a function of hole depth, entrance radius and surface roughness.

Keywords: Micro cutting tool, EDM, parametric study.

1. INTRODUCTION

Conventional machining processes are less popular in the area of micro fabrication. One of the main reasons for this is the unavailability of adequate cutting tools with high dimensional accuracy. Tool grinding process fails to reduce the size of cutting tools beyond some particular limit because of tool rigidity issues. Many alternative processes are tried for cutting tool fabrication including Focused ion beam machining (FIB) and laser machining. Compared to all these processes, micro electro discharge machining can be a promising technique for micro cutting tool fabrication because of its key features like force free machining, capability of fabricating very small features etc. Many researchers have employed micro EDM for fabrication of variety of conventional cutting tools. Perveen et al. [1] fabricated micro tools for grinding of BK7 glass with different geometries (D-type, triangular and square) using micro EDM utilizing a block with three V slots in different angles in it. Chern et al. [2] fabricated tungsten carbide tools with a diameter down to 31 m using methods of micro EDM. Egashira et al. [3] fabricated gun barrel type cemented tungsten carbide drilling tool using the principle of wire electro discharge grinding (EDG). PCD tools with form accuracy and edge sharpness in the order of 1 µm are fabricated using wire EDG on cemented carbide with 90 nm grain size [4, 5]. Even though the capability of fabricating very small cutting tool by EDM process is proved by different researchers, they have not emphasized on the shape distortions and dimensional inaccuracies in the fabricated feature because of tool electrode wear and inaccuracies due to side sparking. To minimize the inaccuracies in cutting tool fabrication using EDM, the fabrication process has to be studied in depth to understand the relationship between the machining parameters and characteristics of the machined surface. Moreover, compared to previous parametric studies on diesinking EDM [6, 7], here only a portion of the tool is coming to contact with the workpiece at an instant. This may change the behavior of tool erosion and side sparking which cannot understand from the previous research studies. In this paper, a micro tool fabrication method employing die sinking EDM is analyzed extensively with the help of a parametric study and a micro tool is fabricated using the optimum machining parameters.

Die sinking EDM is employed for micro tool fabrication in such a way that a rod of 1 mm initial diameter is cut in to a four flute end mill tool by plunging the tool at specific locations according to the tool design. One of the main challenge is to keep the length of the cutting edge uniform at all four locations. This is recognized as a challenge because of the inevitable tool wear during EDM. Along with this, the surface quality of the tool has to be high which affects quality of the machined surface. Fig. 1 explains the tool fabrication process. It has 3 steps (1) EDM milling, which fabricates a square edge micro end mill tool, (2) block EDG, which prepares the die-sinking electrode and (3) die-sinking EDM, which is responsible for a curve edge tool with positive rake angle, and lesser side rubbing. To standardize the tool fabrication a process a parametric study has been designed and executed.

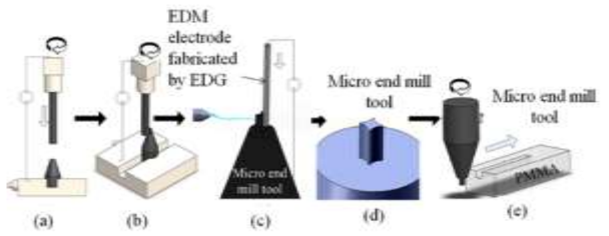

Fig. 1 Schematic diagram of tool fabrication process by EDM (a) Flattening of WC workpiece from the top (b) fabrication of square edge micro end mill tool by EDM milling (c) fabrication of curve edge micro end mill tool by die sinking EDM (d) curve edged micro end mill tool and (e) machining of micro channels on PMMA by the fabricated micro tool [8]

2. EXPERIMENT DETAILS

One of the popular materials for micro cutting tools is tungsten carbide, the same material can be effectively used as an EDM

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tool electrode with comparatively small tool erosion rate. To replicate the tool fabrication process, a tool electrode of 0.3 mm (Tungsten carbide) is plunged to the side surface of a tungsten carbide block. After finding the edge of the block using contact probe, the tool electrode moved half of the diameter inside and moved down to a depth of 1mm from the surface. This cavity resembles the flank face of tool in the cutting tool design. After reaching to the intended depth, tool is moved up and the bottom portion is flattened out using block EDG. After flattening, tool moved to the next location followed by setting up of surface zero coordinate and second set of machining parameters are set for machining. An experimental plan is prepared using Box-Behnken central composite method as shown in Table 2 [9]. Areal surface roughness (Sa), i.e., averaged surface roughness value for an area is measured on the internal surface of the cavity using 3D non-contact profilometer with a 20X zoom lens. After completing the experiments, workpiece is thoroughly cleaned. The profile of the cavity is captured by SEM. Radius of the entrance section and length of the machined cavity is measured. The experimental set up is shown in Fig. 2. Details of the electrodes and dielectric fluid is given in Table 1.

Table 1: Experiment details

Electrode material	Tungsten Carbide (WC) (-ve)
Workpiece material	Tungsten Carbide (WC) (+ ve)
Electrode diameter	300 (µm)
Dielectric fluid	EDM-3 oil

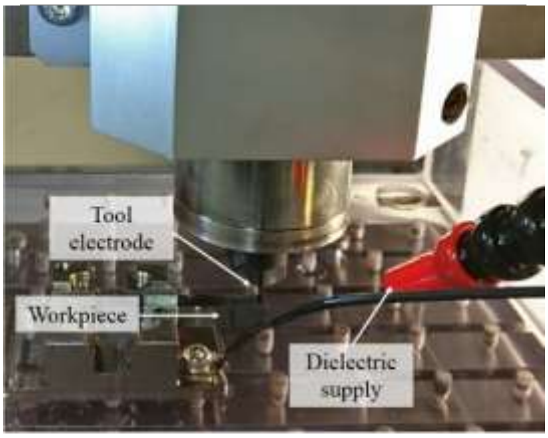

Fig. 2 Experimental set up

1. RESULTS AND DISCUSSION

17 cavities are machined according to the experimental plan with different machining parameters. SEM images revealed noticeable changes in the surface quality, cavity profile and dimensions. The fit summary is recommended that the model is statistically significant for the analysis of the responses. The analysis carried out using Analysis of Variance (ANOVA) tool. Test for lack of fit shows insignificant which is desirable for the model. The final equations (1-3) for the responses according to the analysis gives the relationship between machining parameters and the characteristics of the machined surfaces.

$$Entrance\ Radius,\ R_i = 0.16 - 3.61E\text{-}04 \times V + 6.58E\text{-}03 \times C - 2.30E\text{-}07 \times S + 2.47E\text{-}05 \times V \times C - 1.31E\text{-}08 \times V \times S + 1.03E\text{-}06 \times C \times S + 2.337E\text{-}06 \times V^2 - 4.57E\text{-}04 \times C^2 - 7.40E\text{-}010 \times S^2 \quad : R^2=0.9255 \quad (1)$$

$$Hole\ depth,\ D = 0.13 + 0.016 \times V + 0.04 \times C + 1.40E\text{-}05 \times S - 4.69E\text{-}04 \times V \times C + 3.36E\text{-}07 \times V \times S - 4.90E\text{-}07 \times C \times S - 7.14E\text{-}05 \times V^2 - 7.13E\text{-}03 \times C^2 + 9.004E\text{-}09 \times S^2 \quad : R^2=0.9742 \quad (2)$$

$$Surfaceroughness,\ S_a = 11.36 - 0.12 \times V - 0.25 \times C - 1.34E\text{-}03 \times S + 4.30E\text{-}03 \times V \times C + 1.96E\text{-}05 \times V \times S - 2.158\text{-}04 \times C \times S + 3.46E\text{-}04 \times V^2 + 0.15 \times C^2 + 1.38E\text{-}07 \times S^2 \quad : R^2=0.7425 \quad (3)$$

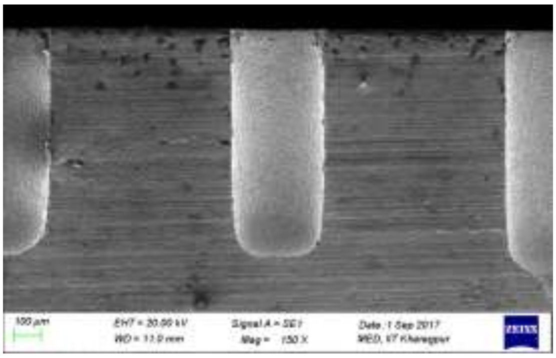

Fig. 3 SEM image of the machined cavity with machining parameters as V=100 V, C= 10 nF

Table 2: Experiment design and responses

S. No	Parameters			Responses		
	V (volt)	C [coded (nF)]	S (rpm)	Ri (mm)	D (mm)	Sa (µm)
1	100	6 (400)	2800	0.192	0.779	7.83
2	120	4 (10)	200	0.183	0.877	5.228
3	120	6 (400)	1500	0.201	0.683	8.23
4	80	6 (400)	1500	0.19	0.760	8.967
5	100	4 (10)	1500	0.181	0.915	4.678
6	100	4 (10)	1500	0.180	0.883	5.836
7	80	4 (10)	200	0.176	0.867	6.055
8	120	2 (0.1)	1500	0.178	0.969	2.758
9	100	4 (10)	1500	0.185	0.906	4.614
10	100	6 (400)	200	0.187	0.788	8.049
11	100	2 (0.1)	200	0.168	0.999	3.308
12	100	2 (0.1)	2800	0.183	0.994	5.333
13	100	4 (10)	1500	0.179	0.922	3.242
14	80	2 (0.1)	1500	0.181	0.972	4.183
15	120	4 (10)	2800	0.184	0.895	6.267
16	100	4 (10)	1500	0.178	0.890	8.017
17	80	4 (10)	2800	0.179	0.920	5.049

V – voltage, C – capacitance, S – tool rotation, Ri – entrance radius, D – hole depth, Sa – areal surface roughness

The entrance diameter determines the overcut (difference between the tool diameter and hole diameter), tool, hole depth determines the available tool length and surface roughness value will be responsible for the surface quality of the hole. All these factors will affect the dimensional accuracy and surface quality of the cutting tool to be fabricated using EDM. Overcut due to side sparking is the main reason for the increase in entrance radius. Fig. 4, Fig. 5 and Fig 6 are plotted using Eq. (1-3). They show the interaction effect of the selected process parameters on the response parameters. It is observed from the slope of the response surfaces that capacitance has the highest effect on the response parameters followed by voltage.

Entrance radius: Fig. 4 (a, b) shows the response surfaces of entrance radius of the hole with respect to voltage, capacitance and spindle speed. Increase in capacitance and voltage increases the total discharge energy in side sparking which will be responsible for the increase in entrance radius in which capacitance is the prominent parameter which controls the overcut value. It is evident from the analysis that source voltage and tool rotation play very little role in the overcut at the entrance section. Tool rotation helps in removal of debris from the machining zone and reduces re-solidification of the removed material. As the entrance radius increases, the cutting edge length of the fabricated tool will be reduced. So to keep the errors to minimum, entrance radius length has to be minimized.

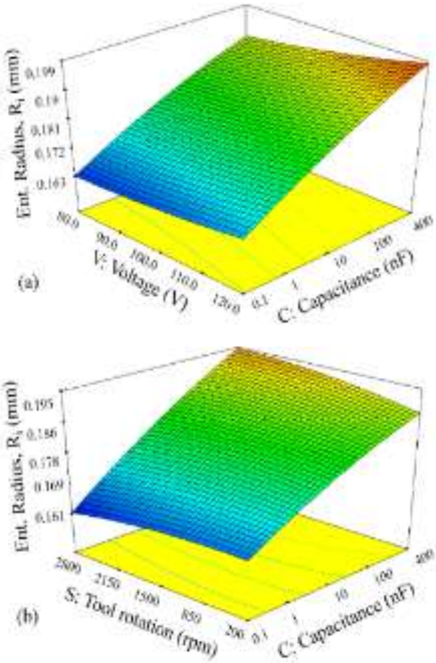

Fig. 4 Effect of (a) Voltage – Capacitance and (b) Tool rotation – Capacitance on entrance radius (R_i)

Hole depth: While fabricating micro tool using die sinking EDM, depth of the cavity or hole determines the length of the micro cutting tool. During machining the tool electrode undergoes continuous tool erosion so that the length of the electrode is reduced. Therefore, the bottom surface of tool electrode will never reaches up to the intended depth. As discharge energy increases, tool erosion rate also increases so that the difference between intended depth and actual depth becomes larger. From Fig. 5 (a, b), it is clear that the hole depth is severely affected by the increase in capacitance and voltage in which capacitance has the maximum influence on the tool erosion rate. This error in hole depth will replicate in the cutting tool as reduced cutting tool height or available cutting tool length.

Surface roughness: Increase in discharge energy will result in large crater size on the machined surfaces, which reduces the surface quality. From Fig. 6 (a, b) it is evident that in this case also, capacitance plays the prominent role in controlling surface roughness of the machined surface. At high capacitance, material removal is high. High tool rotation helps in removal of debris and clear the working gap for the next sparking. Hence, little reduction in surface roughness is observed with increase in tool rotation at high capacitance. However, the effect of tool rotation at low capacitance is different than that of at high capacitance. This may be due to low energy spark rotating at high speed which results in scattering of spark energy. Surface quality of the cavities determines the surface quality of the cutting tool to be fabricated, so that the capacitance values has to be kept minimum for lower surface roughness. The measurement of surface roughness at an internal area of the cavity using laser is severely affected by shadowing effect which introduces some measurement errors in the result. This may be the reason for reduced R^2 value for surface roughness.

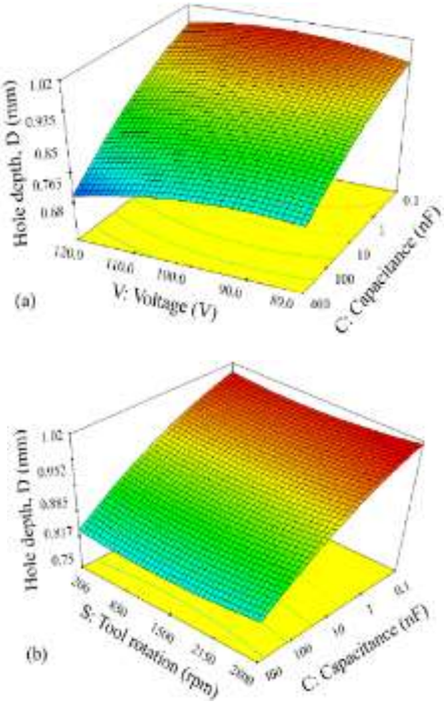

Fig. 5 Effect of (a) Voltage – Capacitance and (b) Tool rotation – Capacitance on hole depth (D)

After parametric study, optimum machining parameters are calculated using Design-expert® software based on Derringer and Suich multiple response method [10]. It optimizes the objective function or the desirability function (d_i) by transforming the estimated response to desirability values. The desirability function involves transformation of each estimated response variable $R_i$to a desirability value d_i, where $0 <= d_i <= 1$. Combination of factor values with highest desirability is taken as the optimal settings for machining. The constraints are given such way to minimize the entrance radius, achieve a target depth of 1 mm, and minimize the surface roughness. After analysis, the optimal parameters are calculated as voltage (V) = 107.6 V, capacitance (C) = 0.1 nF, and speed (S) = 200 rpm with a desirability value of 0.937. The optimum output parameters are, entrance radius (R_i) = 0.167mm, hole depth (D)=0.998 mm, Surface roughness (S_a)=2.83 µm.

4. FABRICATION OF MICRO END MILL TOOL

Using the optimum results from the experiments, a WC micro tool has been fabricated. An end mill tool of 1 mm diameter is selected and the top is flattened using EDG process. Then, the micro tool shape has been fabricated on the top of the tool using die sinking EDM as explained in Fig. 1. The available tool length of the fabricated tool is uniform in all directions and the cutting edge length is near to the intended value of 75 µm. The fabricated tool is shown in Fig. 7. The fabricated tool is successfully used to machine channels on poly methyl methacrylate (PMMA) surface.

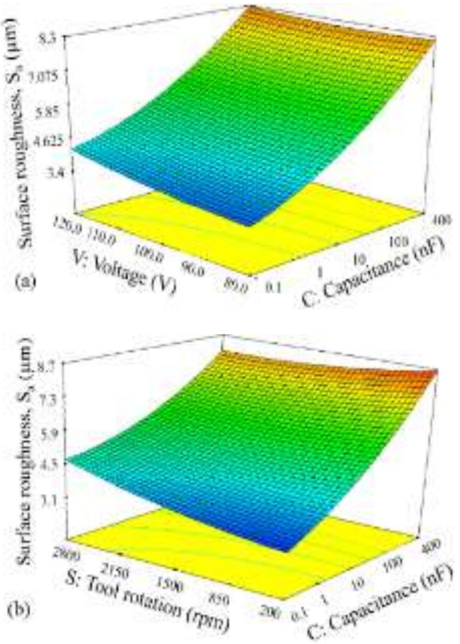

Fig. 6 Effect of (a) Voltage – Capacitance and (b) Tool rotation – Capacitance on surface roughness (Sa)

5. CONCLUSIONS

The following conclusions are drawn from the present study.

1. A process employing die sinking EDM is established for fabrication of micro cutting tools.
2. Effect of machining parameters like voltage, capacitance and spindle speed on entrance radius of the cavity, depth, and surface finish is studied.
3. Analysis of the response surfaces revealed that capacitance has the maximum influence on entrance radius, hole depth, and surface roughness followed by voltage and tool rotation.
4. Increase in capacitance elevates the discharge energy level which is responsible for increased overcut, tool erosion rate and crater size during machining. This results in larger entrance radius, smaller hole depth and higher surface roughness.
5. Surface roughness is further affected by tool rotation in which the roughness value increases slightly with increase in tool rotation speed at low capacitance level. This trend reverses at high capacitance level in which the roughness decreases as tool rotation speed increases.
6. Optimum level of process parameters are voltage = 107.58 V, capacitance = 0.1 nF, and speed = 200 rpm for minimizing the entrance radius, achieving a target depth of 1 mm, and minimizing the surface roughness.
7. A micro end mill tool with four cutting edges is fabricated using the optimum machining conditions.

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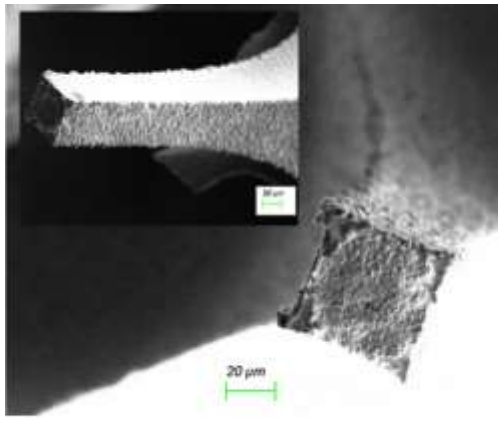

Fig. 7 Micro end mill tool fabricated using the optimum process parameters (inset figure shows length-wise tool)

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