Micro Slot Generation by µ-ED Milling

H K Dave¹, M K Mayanak², S R Rajpurohit³ and V J Mathai⁴
¹,²,³,⁴ Department of Mechanical Engineering, S V National Institute of Technology, Ichchhanath, Surat – 395 007, Gujarat, India
E-mail: shilpesh18@gmail.com

Abstract: Micro electro discharge machining is one of the most widely used advanced micro machining technique owing to its capability to fabricate micro features on any electrically conductive materials irrespective of its material properties. Despite its wide acceptability, the process is always adversely affected by issues like wear that occurred on the tool electrode, which results into generation of inaccurate features. Micro ED milling, a process variant in which the tool electrode simultaneously rotated and scanned during machining, is reported to have high process efficiency for generation of 3D complicated shapes and features with relatively less electrode wear intensity. In the present study an attempt has been made to study the effect of two process parameters viz. capacitance and scanning speed of tool electrode on end wear that occurs on the tool electrode and overcut of micro slots generated by micro ED milling. The experiment has been conducted on Al 1100 alloy with tungsten electrode having diameter of 300 µm. Results suggest that wear on the tool electrode and overcut of the micro features generated are highly influenced by the level of the capacitance employed during machining. For the parameter usage employed for present study however, no significant effect of variation of scanning speed has been observed on both responses.

Key words: Micro ED milling, Capacitance, Scanning speed, End wear on tool electrode, Overcut

1. Introduction
Micro manufacturing techniques have become so important due to increasing demand for micro parts and structure of various industries. Micro structures, including micro holes, micro slots, micro shafts, and micro gears are widely used micro products required in industries. Micro-slots or micro-channels are one such type of feature which has immense applications in the fabrication of miniature devices, micro-fluidic devices, micro-heat-sinks, or heat exchangers, etc. [1, 2]. Micro electro discharge (ED) milling is a variant of the Micro EDM, where a rotating tool with a scanning motion is used to generate micro slots in workpiece along a prescribed feature. This tool motion is achieved in a plane perpendicular to the workpiece surface and passing through the centre line of the micro slot along its length during the to and fro motion, the tool electrode also moves in Z direction at the same time.

Despite of wide popularity of Micro ED machining process, it has some limitations like tool wear, accuracy of generated features, relatively low material removal rate, specific tool shape, surface finish etc. Tool wear is an undesirable effect in micro electro discharge machining process, which adversely affects the quality of generated micro features. Even though, micro size features are difficult to generate by conventional as well as advanced mechanical based micro machining techniques, many researchers have tried to apply them for the generation of micro featured like slots. Murali et al. [3] studied Fast EDM and gravity assisted micro EDM for the generation of micro groves by a foil as electrode. Yan et al. [4] generated micro grooves having various cross section like rectangular,
triangular, circular and semi closed by ED milling. Karthikeyan et al. [5] proposed a new way to measure the volume of material removed from workpiece and tool with an aid of design software. Hung et al. [6] fabricated micro flow channels in metallic bipolar plate by µ ED milling. Mehfuz et al. [7] investigated the effect of process parameter on tool wear ration and MRR on micro ED milling. Lim et al. [8] used WEDG to fabricate the micro electrode with high dimensional accuracy. Mohri et al. [9] fabricated micro electrode which is driven through the control slit between two electrically isolated plates. Tsai et al. [10] investigated the electrode wear of various materials in micro EDM. Yan et al [11] reported the application of the machine vision system to measure the tool wear. Li et al. [12] proposed a new wear compensation method based on scanned area in each layer machining. Bissacco et al. [13] measured tool wear during on-machine-measurement with help of laser scan micrometer. Yu et al. [14] fabricated 3D cavities using layer by layer machining which leads to uniform wear of tool. Zilong et al. [15] proposed a reversible micro EDM to fabricate micro structure. During the fabrication of micro slots by µ ED milling, effect of various process parameters on overcut and tool wear rate has been studied by Dave et al. [16].

µ ED milling is a variant of the µ ED machining process, in which tool will be scanned over the length of micro slots to be generated which needs to be investigated. In the present study, effect of scanning speed and capacitance has been investigated on end wear of tool electrode and quality of micro slots generated in terms of overcut.

2. Experimental Details
All the experiments were performed on Hyper 15 C multipurpose micro machine shown in Figure 1. The machine tool has a positional accuracy and repeatability of ±5 and ±7 µm, respectively. This machine is able to perform various kind of operation like micro milling, micro turning, micro EDM and wire EDG. Besides, process variants like micro ED milling and micro ED drilling can be performed with suitable tool movements.

![Figure 1. Experimental set up](image)

Split Al 1100 alloy block has been used as workpiece material having a dimension 40 mm x 35 mm x 6 mm. Pure tungsten rod of 300 µm diameter and length of 10 mm has been fabricated using the foil and wire based EDM method suggested by Dave et al. [17]. Figure 2(a) shows the split workpiece on which linear slot has been fabricated such that the slot is equally divided between both parts. Figure 2(b) shows the tool electrode after dressing using wire EDM process. The physical properties of the workpiece and tool material are given in Table 1.
Table 1. Properties of Al1100 and tungsten

|                      | Al 1100       | Tungsten     |
|----------------------|---------------|--------------|
| Density              | 2.7 g/cm³     | 19.25 g/cm³ |
| Melting point        | 660 °C        | 3410 °C      |
| Crystal structure    | FCC           | BCC          |
| Thermal conductivity | 237 Wm⁻¹ K⁻¹ | 173 Wm⁻¹ K⁻¹|

Table 2. µ ED milling process parameters

| Parameters             | Levels                   |
|------------------------|--------------------------|
| Variable               | Scanning speed (mm/min)  | 40, 50, 60, 70 |
|                        | Capacitance (pF)         | 33, 100, 1000, 10000 |
| Constant               | Voltage (V)              | 100           |
|                        | Spindle speed (rpm)      | 500           |
|                        | Layer depth (µm)         | 10            |
|                        | Electrode diameter (µm)  | 300           |

In the present experimental work two input parameter viz. capacitance (C) in pF and scanning speed (S) in mm/min have been varied at four levels. Table 2 lists process parameters selected for present experiment along with values during the µ ED milling. Micro slots of 4 mm length and 300 µm depth were made on split block of Al 1100 using tungsten as an electrode. Micro slots has been generated in such a way that central line of the slot and split line on the workpiece coincide with each other.

The end wear that occurred on the electrode during µ ED milling is calculated by measuring the length of the electrode before and after milling the micro slot. Quality of the micro slots in terms of overcut by µ ED milling has been measured by radial overcut of the micro slots. The equations used for the calculations of these responses are given as below.

\[
TEW = L_{bm} - L_{am}
\]

\[
OC = \frac{W - D_e}{2}
\]

Where, \(TEW\) = Tool end wear, \(L_{bm}\) = Length of the tool before machining, \(L_{am}\) = Length of the tool after machining, \(OC\) = Radial overcut of the micro slots, \(W\) = Width of the micro slots, \(D_e\) = Diameter of the electrode.
3. Results and Discussions
Table 3 shows the details of both the response characteristics along with the experimental condition used for the experimentations.

| Exp. No. | S (mm/min) | C (pF) | TEW (µm) | OC (µm) |
|----------|------------|--------|-----------|---------|
| 1        | 50         | 33     | 48        | 62.5    |
| 2        | 50         | 100    | 207       | 88      |
| 3        | 50         | 1000   | 247       | 145.5   |
| 4        | 50         | 10000  | 255       | 156.5   |
| 5        | 40         | 10000  | 230       | 68.5    |
| 6        | 50         | 10000  | 255       | 62.5    |
| 7        | 60         | 10000  | 238       | 77      |
| 8        | 70         | 10000  | 239       | 64.5    |

3.1 Effects on Tool end wear
Being an electro discharge process, the material gets eroded from the tool electrode also, however with a relatively lower rate than that of the workpiece. At macro level electro-discharge machining process, where the tool is anode, the tool wear is relatively less because of the protection provided by the thick layer of carbon produced because of the dissociation of the hydrocarbon oils. But in the case of micro-EDM where the tool electrode is usually cathode, the carbon deposit will be relatively less, which eventually results into higher electrode wear.
From figure 3 (a, b) it can be observed that capacitance has significant effect on end wear of tool electrode, however scanning speed does not find much significant effect on the tool end wear for selected range of value. Experimental results suggest that tool end wear increases with increment in capacitance (figure 3 (a)). At very low capacitance, tool end wear is less due to less pulse energy. Electrode wear is more at higher capacitance because of the more pulse energy.

3.2 Effects on Overcut

Figure 4 suggests that capacitance has significant effect on overcut of micro slots, however scanning speed does not have much significant effect in the present range. Experimental results suggest that overcut increases with increment in capacitance. At higher capacitance, over cut is higher due to increase in energy discharge. Higher discharge energy will results into more material removal relatively which leads to higher overcut.
Figure 4 (a) Effect of the scanning speed on overcut, (b) Effect of the capacitance on overcut

Figure 5 (a-d) shows image of the micro slots produced by varying capacitance at 50 mm/min scanning speed. It can be seen from the figure that quality of the micro slots is deteriorates with increment in the capacitance. Discharge energy is a function of the capacitance. Due to low capacitance, less discharge energy will be utilized to remove the material in the form of smaller crater. Higher discharge energy results into higher material removal in the form of the relatively bigger craters and hence more overcut is observed.

Figure 5 (a-d) Micro slots generated by varying different capacitance at S = 50 mm/min

Figure 6 (a-d) shows image of the micro slots produced by varying scanning speed at 10000 pF capacitance. It is observed from the figure that quality of the micro slots does not get affected by variation in scanning speed.
Figure 6 (a-d) Micro slots generated by varying different scan speed at C = 10000pF

4. Conclusions
Effect of capacitance and scanning speed on responses like tool end wear and overcut during μ ED milling process has been studied. Basic conclusions drawn are as below:
- As capacitance increases both the responses viz. tool end wear and overcut increases due to increment in discharge energy;
- Scanning speed does not have significant effect on both responses within selected range;
- Quality of micro slots deteriorates with increase in capacitance.

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