Machining of Micro Slots in Titanium using Micro Electrical Discharge Milling

Siddhartha Kar* and Promod Kumar Patowari

Department of Mechanical Engineering
National Institute of Technology Silchar, Assam - 788010, India

Abstract

Micro milling is an important process for fabricating complex three-dimensional microcavities. This paper presents an experimental study on machining of micro slot by micro electrical discharge milling (µED-milling) process on Titanium Grade 2 alloy using tungsten rod as tool electrode. The effect of process parameters such as layer thickness, tool rotation speed, and feed rate are investigated on the performance measures in the process. The performance measures dimensional deviation and machining time are evaluated to observe the efficiency of the µED-milling process in fabricating micro slots. The process parameters are optimized for lower machining time and dimensional deviation. Using the optimized parametric condition, a uniform slot is machined. Tool wear compensation, using to and fro machining approach, is also considered while machining this slot. Finally, a micro square pillar is machined by combining micro milling process and tool wear compensation approach using layer by layer machining strategy. The dimensional accuracy and machining efficiency of the micro slot and micro square pillar justify µED-milling process as a suitable method for fabrication of three-dimensional microfeatures on Titanium.

Keywords: Micromachining, Micro Slot, Electrical Discharge Milling, Tool Wear Compensation, Dimensional Deviation, Machining Time, Square Pillar.

1. INTRODUCTION

Micromachining is a demanding field in the present day manufacturing scenario due to the growing rise in the use of micro parts and micro components. Various engineering domains such as aerospace, bio-medical, automotive and electronics etc., are largely dependent on the production of dimensionally accurate and precise micromachined products. Micromachining, essentially produces micro parts, micro die/mold, etc., wherein at least one of the machined dimension is <1 mm. Several manufacturing processes such as LBM (laser beam machining), EBM (electron beam machining), IBM (ion beam machining), µUSM (micro ultrasonic machining), LIGA (Lithography, Electroplating, and Molding), µECM (micro electrochemical machining), µEDM (micro electrical discharge machining), etc. are capable of performing micromachining on a large spectrum of materials. Among these micromachining processes, µEDM had been extensively performed over the last two decades due to its capability of machining electrically conductive materials irrespective of their hardness and ease of use. Further, the non-contact mechanism between the tool and workpiece allows precise machining without any chatter and vibration. In µEDM, material is removed due to melting and vaporization owing to the impingement of spark in the shortest distance between the tool electrode and workpiece [1].

Micromachining is also possible by conventional machining processes involving cutting tool but the cutting tool needs to be harder than the workpiece material. Introduction of tungsten, tungsten carbide, and hard coating based tool insert has made possible to micromachine materials such as titanium and its alloys. However, manufacturing of such microtool is a daunting task which involves a lot of effort and cost. The problem of burr formation is also a demerit in conventional micromachining.

Micromilling is a machining process used for fabrication of complex three dimensional (3D) cavities. Beside z-directional movement of the cutting tool, the x-directional and y-directional movement of the worktable allows machining of 3D micro cavities with ease. Micro electrical discharge milling (µED-milling) is a variant of µEDM that can machine complex 3D micro cavities, wherein the material removal takes place by µEDM phenomenon and 3D contouring motion is taken care by x and y directional movement of worktable. The µEDM process eliminates the use of conventional milling tools that have intricate shapes and requires intense labor in manufacturing. Rather, it uses simple cylindrical tool for micromilling, thus saving time and manufacturing cost of milling tool.

Recently, a lot of focus is given on micromachining of materials such as stainless steel, titanium and their alloys which are extensively used in biomedical implants. Micromachining of titanium and its alloys is very difficult by conventional use of cutting tool due to their high hardness. The use of µEDM in micromachining of titanium had been reported by many researchers. Moses and Jahan [2] successfully fabricated micro-features such as micro holes, micro slots and patterns on titanium grade 5 alloy (Ti-6Al-4V) using µEDM. They observed debris particles getting attached to the surface and edges of the micro-features. D'Urso et al. [3] performed µEDM drilling on stainless steel and tungsten carbide using brass and tungsten carbide electrodes. They observed various properties of tool and workpiece materials such as electrical resistivity, melting point and thermal conductivity significantly affecting the machining process. They also proposed an overall process index based on process parameters and material properties. Jahan et al. [4] performed µEDM drilling on tungsten carbide using RC (resistance-capacitance) and transistor-type pulse generator. They found RC type generator to be more appropriate for fabricating microstructures with superior dimensional accuracy and surface finish. Kuriachen and Mathew [5] found significant influence of process parameters such as voltage, capacitance, rotation speed and feed rate in µED-milling of Ti-6Al-4V. They observed the formation of recast layer on the milled surface and also noted the migration of tool material to the machined surface. Later, Kuriachen and Mathew [6] performed µED-milling of Ti-6Al-4V in silicon carbide (SiC) powder mixed dielectric, wherein capacitance and powder concentration were the most

*Author to whom correspondence should be made, Email: siddkar.nita@gmail.com

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significant process parameters. The micro slots were exposed to cracks and holes at the two ends despite the formation of an even modified layer of tungsten and SiC. Jafferson et al. [7] investigated the effect of non-electrical parameters such as layer thickness, rotation speed, and feed rate on material removal rate and relative tool wear in µED-milling of stainless steel. Higher feed rate and rotation speed were recommended for obtaining maximum material removal rate and minimum relative electrode wear. Layer thickness also influenced both the responses significantly and layer by machining strategy was able to dress the tool electrode automatically.

From the literature, it can be seen that besides electrical parameters of µEDM, non-electrical parameters also play a big role in attaining higher machining efficiency and dimensional accuracy. Very few work has been reported on the µED-milling of titanium and its alloys. As per the literature, no work has yet been reported on µED-milling of titanium grade 2 alloy. Exploring all these gaps, the present work aims to study the effect of variation of layer thickness, rotation speed and feed rate on machining time and dimensional deviation in fabricating micro slots on titanium grade 2 alloy using µED-milling process.

2. MATERIALS AND METHODS

The experiments are conducted in a µEDM machine (Model: Hyper-15, Make: Sinergy nano systems, Mumbai, India) shown in Fig. 1. A cylindrical tungsten rod of diameter 515 µm is taken as the tool electrode (Fig. 2) due to its high melting temperature and hardness. Titanium grade 2 alloy is chosen as the workpiece material; wherein micro slots are to be fabricated by µED-milling process. Hydrocarbon oil is used as the dielectric medium, and jet flushing is applied in the machining zone to avoid deflection of the tool. In this study, electrical parameters of µEDM such as voltage, capacitance, and polarity are kept fixed whereas non-electrical parameters such as layer thickness, feed rate, and tool rotation speed are varied. The variable and fixed process parameters of this experimentation are depicted in Table 1. The experimentation is conducted in three phases. In the first phase, layer thickness is varied while in the second and third phase feed rate, and rotation speed is varied while keeping all other process parameters fixed. Machining time is recorded for each combination of process parameters during experimentation. After experimentation, optical micrographs of the micro slots are taken by a Trinocular Metallurgical Microscope (Make: Leica, Model: DM 2500M) for analyzing the dimensional deviation of the fabricated slots.

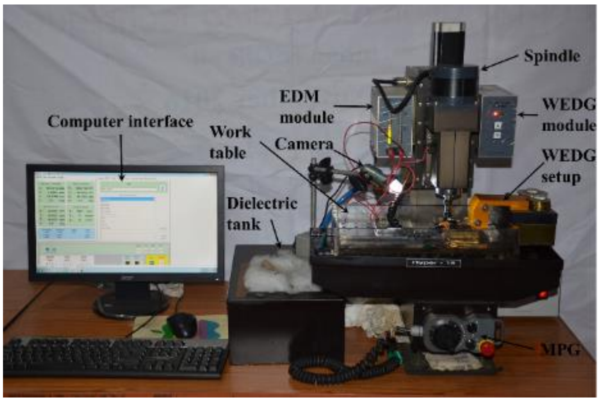

Fig. 1. Photographic view of µEDM setup (Model: Hyper-15; Make: Sinergy nano systems, Mumbai, India)

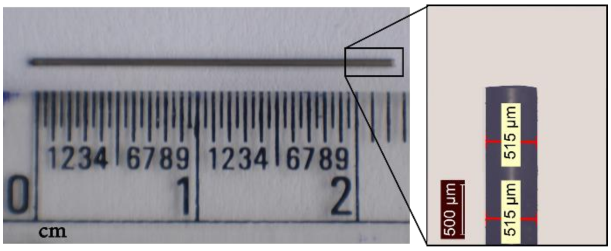

Fig. 2. Tungsten cylindrical micro rod used as tool electrode

Table 1: Variable and fixed process parameters

Variable parameters with their levels	
Parameter	**Level**
Layer thickness, LT (µm)	50, 60, 70, 80, 90, 100
Tool rotation speed, TRS (rpm)	500, 1000, 1500
Feed rate, FR (µm/s)	10, 15, 20
Fixed parameters with their levels	
Parameter	**Value**
Voltage (V)	100
Capacitance (pF)	10000
Polarity	Tool (-ve); Workpiece (+ve)
Dielectric medium	Hydrocarbon oil
Flushing type	Jet flushing

3. RESULTS AND DISCUSSION

Figure 3 shows the micro slots fabricated on Ti grade 2 alloy using µED-milling process. The width of the slots is observed to diminish after a certain distance due to the effect of tool wear. The effect of the non-electrical process parameters: layer thickness, feed rate, and tool rotation speed are discussed in the subsequent sub-sections.

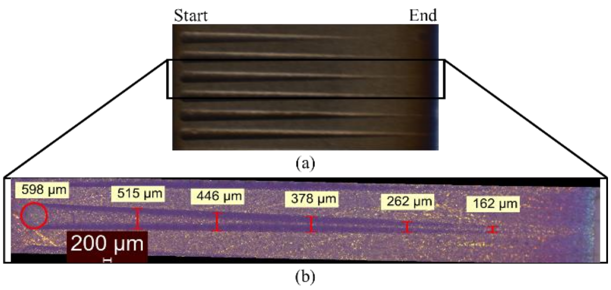

Fig. 3. Micro slots on titanium grade 2 alloy at different layer thickness a) Photographic view and b) Microscopic image of a micro slot

3.1 Layer thickness (LT)

µED-milling is performed in several layers, wherein each layer is assigned a particular depth of cut known as layer thickness. Optimum selection of layer thickness is an important criterion for µED-milling because lower value of layer thickness reduces process efficiency whereas higher value causes short circuiting between the two electrodes, deflect the micro tool and may eventually break the tool. Figure 4 (a) shows the effect of layer thickness on the machining time keeping the rotation of tool, feed rate and cutting length (CL) fixed at 1000 rpm, 15 µm/s and 15 mm respectively. With the increment in layer thickness the machining time increases as the tool is exposed to a larger volume of work material in the machining zone. Figure 4 (b) shows the effect of layer thickness on the variation of slot width at 5 mm distance from the start of µED-milling. The width of the micro slots increases with the increment in layer thickness due to the rise in the length of the tool in the locality of generating spark and eroding material from the workpiece in µED-milling. No cases of tool deflection and breakage are recorded which justifies the undertaken range of layer thickness values within working condition for the parametric conditions considered in this study.

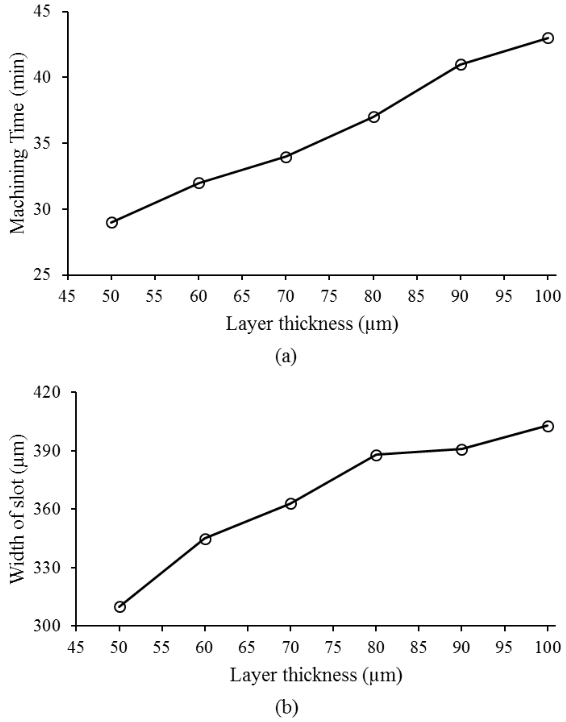

Fig. 4. Effect of layer thickness on a) machining time and b) width of slot

3.2 Feed rate (FR)

Feed rate in µED-milling process regulates the time required by the tool electrode for maintaining sufficient inter-electrode gap between two successive discharges. Figure 5 shows the effect of feed rate on machining time keeping layer thickness, rotation speed and cutting length fixed at 50 µm, 1000 rpm and 10 mm respectively. With the increase in feed rate the tool retracts back and moves forward faster after undergoing short circuit, thus reducing the idle time or non-machining time and resulting in a reduction of the machining time.

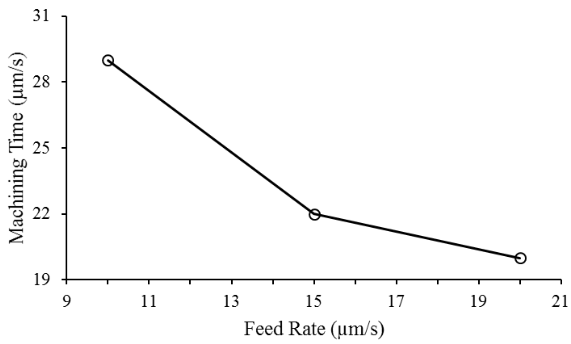

Fig. 5. Effect of feed rate on machining time

3.3 Tool rotation speed (TRS)

Rotation of tool electrode plays an important part in stabilizing the µED-milling process. It produces a centrifugal force in the machining zone which circulates the dielectric fluid in the machining zone and helps in flushing away of the debris. Rotation of tool electrode also reduces the wobbling effect of the tool. Figure 6 shows the effect of TRS on machining time keeping layer thickness and feed rate fixed at 15 µm/s respectively. The machining time decreases with the increase in TRS due to higher spin stability imposed at a higher speed which prevents short circuit and enacts normal discharge [8].

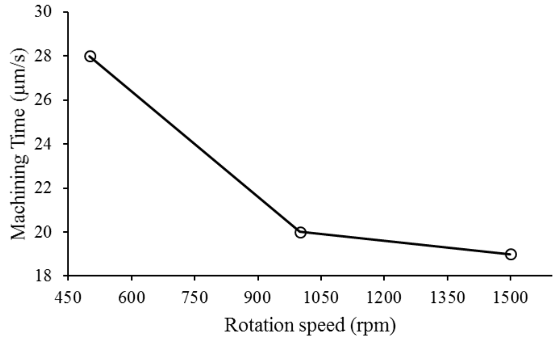

Fig. 6. Effect of rotational speed on machining time

3.4 Fabrication of uniform slot and micro square pillar

From Fig. 3 it can be realized that the width of the slots gradually decreases with the progress of µED-milling. This dimensional deviation of micro slots occurs due to the phenomenon of tool wear. Tool wear is indispensable in all the variants of EDM. To achieve dimensional accuracy, tool wear needs to be compensated as it cannot be diminished altogether. The simplest and traditional way to compensate the effect of tool wear in µED-milling is to apply 'to and fro' scanning method, wherein a micro slot machined from left (start) to right (end) is accompanied by another machining layer of the same slot from right (start) to left (end) and vice versa. This method has been successful in fabricating uniform micro slot by µED-milling. Applying this method, a micro slot is fabricated with layer thickness 50 µm, rotation speed 1500 rpm and feed rate 20 µm/s as shown in Fig. 7. The slot is machined in two 'to and fro' layers. The machining was completed in 102 min with each 'to and fro' layer requiring 51 min. The width of the slot at its two ends and middle is found to be varying between 670 µm to 671 µm. Depth is measured at the two ends and middle of the slot by electrical contact of the tool electrode in reference to a fixed coordinate. Table 2 (a) shows the depth of the micro slot at various points. The low standard deviation (SD) of 4.91 µm in depth across the length of micro slot justifies the application of the 'to and fro' scanning method in compensating tool wear in µED-milling.

Table 2: Variation of depth

a) Uniform slot			
Position	Start	Middle	End
Depth (µm)	112.3	102.6	106.1
SD (µm)	4.91		

b) Micro square pillar				
Corner	1	2	3	4
Depth (µm)	164.3	179.1	190	210.7
SD (µm)	19.53			

Further, a micro square pillar is fabricated by the µED-milling process taking the process parameters of the uniform slot. The total length of tool path is taken as 4 mm, wherein the side length of the square route is 1 mm. The microscopic image of the machined micro square pillar is shown in Fig. 8. Side length of

269 µm square pillar is achieved without any corner effect whereas fillets are clearly visualized in each corner of the square slot. The diameter of one of the fillets is 707 µm (Fig. 8). The fabrication of micro square pillar took 73 min. The depth ranges from 164.3 µm to 210.7 µm at the four corners with an SD of 19.53 µm as shown in Table 2 (b). The occurrence of higher SD in depth may be due to inadequate tool path and positioning error of the tool while making electrical contact in the corner points.

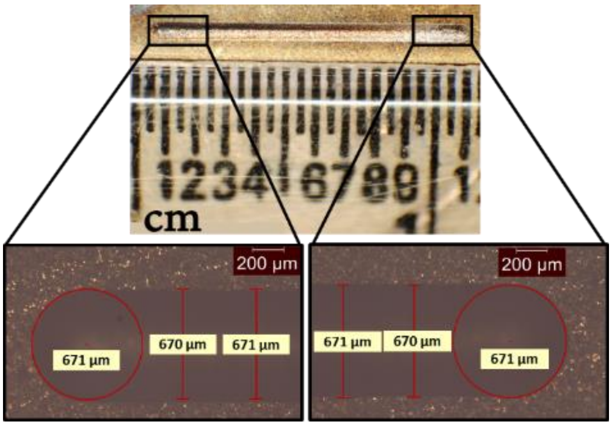

Fig. 7. Uniform slot fabricated by to and fro machining approach

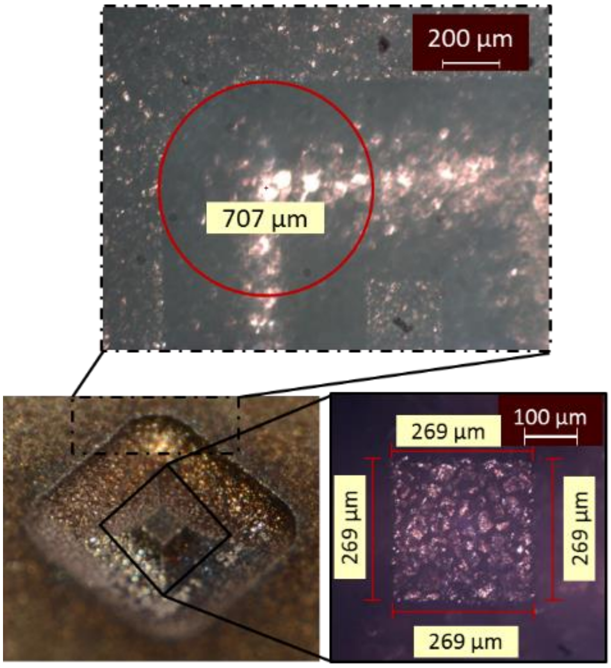

Fig. 8. Micro square pillar fabricated by µED-milling

4 CONCLUSIONS

µED-milling has been successfully used to fabricate micro slots in Titanium grade 2 alloy, otherwise which is difficult to machine by conventional machining processes. A parametric analysis is conducted to investigate the effect of non-electrical process parameters such as layer thickness, feed rate and tool rotation speed on the machining time and dimensional deviation. Further, a uniform micro slot and a micro square pillar are fabricated by taking optimized process parameters. The following conclusions are drawn from this experimentation:

a) Machining time increases with the increase in layer thickness due to the exposure of larger volume of work material in the machining zone.
b) Machining time decreases with the increase in feed rate and tool rotation speed due to minimization of idle time and improved flushing of debris particles respectively.
c) The width of the slot decreases as the µED-milling proceeds and diminishes after a certain distance due to tool wear.
d) To and fro scanning method is employed to negate the effect of tool wear and a micro slot of 10 mm length is fabricated whose width ranges from 670 µm to 671 µm and depth varies from 102.6 µm to 112.3 µm. A lower SD of 4.91 µm for depth justifies the applicability of the 'to and fro' strategy in fabricating uniform micro slot.
e) A micro square pillar of 269 µm side length is fabricated by applying 'to and fro' scanning method with µED-milling. A high SD of 19.53 µm is attained for depth at the four corners due to improper tool route and positioning error of tool.

Future studies may be concentrated on designing optimal tool path and minimizing the effect of tool wear for fabricating 3D cavities with higher dimensional accuracy and precision.

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