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Rapid Biocompatible Micro Device Fabrication by Micro Electro-Discharge Machining

*M. Murali and S. H. Yeo**
School of Mechanical and Production Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798
E-mail: mshyeo@ntu.edu.sg

Abstract. **Fabrication of a biocompatible micro device is predominantly done by silicon micromachining techniques. The lithographic and etching techniques require preparation and the use of masks which are time consuming and costly. Since bio research involves highly complex mechanisms, the modeling and simulation is difficult and experimental study is inevitable. To incorporate frequent design changes and to realize the hardware quickly, fabrication processes, complementary to the silicon micromachining techniques are required. In the present work the feasibility of using micro electro-discharge machining (EDM) for the fabrication of biocompatible microdevice has been studied. Micro channels with feature size as small as 25 µm are realized. The process is further improved by the introduction of ultrasonic vibration of the workpiece and the total time taken for the hardware realization is about 4 hours. The effects of ultrasonic vibration on the roughness of the spark eroded surface has been studied and reported. The potential of using micro EDM for making biocompatible devices for bio experiments is demonstrated and the surface finish achieved is well within the recommended R_z and R_a values of 3.4 and 0.4 µm respectively for biological studies like implant abutment.**

Key Words. **micro-channel, micro EDM, ultrasound, rapid fabrication, biocompatibility**

1. Introduction

Biocompatibility is the ability to exist alongside living things without harming them. It is defined as ''the ability of a material to perform with an appropriate host response in a specific application.'' [1]. It implies that the definition of biocompatibility of a material can vary depending on how the material is used. For example in case of implantation into a tissue, it is desirable that the cells of the tissue treat the material as a part of the tissue to stick to it and grow on it. On the other hand, in applications where the material comes in contact with the bloodstream, it is vital that the blood cells do not stick to it, as this will result in a clot, which could be fatal [2]. With this understanding one can choose an appropriate material for the making of a biocompatible micro device based on the application.

Titanium alloy is one such material being used worldwide for the biomedical applications owing to its biocompatibility [3,4]. The interest of the scientific community in titanium can be traced way back to the beginning of the nineteenth century [5]. Its unique properties such as the high strength to weight ratio and corrosion resistance have made titanium alloy a popular choice for engineering applications [6]. With the development of science and technology and with the recent outburst of research in bio-sciences, titanium alloys are increasingly being used in the biomedical field for both *in vivo* and *in vitro* applications [7–9].

In the fabrication of micro devices using titanium alloy by conventional methods, like drilling, turning and milling, we encounter problems of poor machinability [10]. However, with the help of complementary micromachining technology like micro electro-discharge machining (EDM), micro features can be successfully made on titanium alloy. In this paper we have demonstrated the fabrication of micro channels on titanium alloy using micro EDM. Devices with such micro channel features are required for studies such as DNA separation and detection [11]. The fabrication process is further improved by the introduction of ultrasonic vibration of the workpiece.

2. Theory of Micro EDM and Ultrasonic Vibration

Micro EDM is based on a simple theory, which is as follows. When two electrodes, separated by a dielectric medium, come closer to each other, the dielectric medium that is initially non conductive, breaks down and suddenly becomes conductive. During this period sparks will be generated between the electrodes. The thermal energy released will be used for the material removal by melting and evaporation. By precisely controlling the amount of energy released, it is possible to machine micro features on any electrically conductive material [12]. The material biocompatibility is not impaired by such thermal treatment [13].

*Corresponding author.

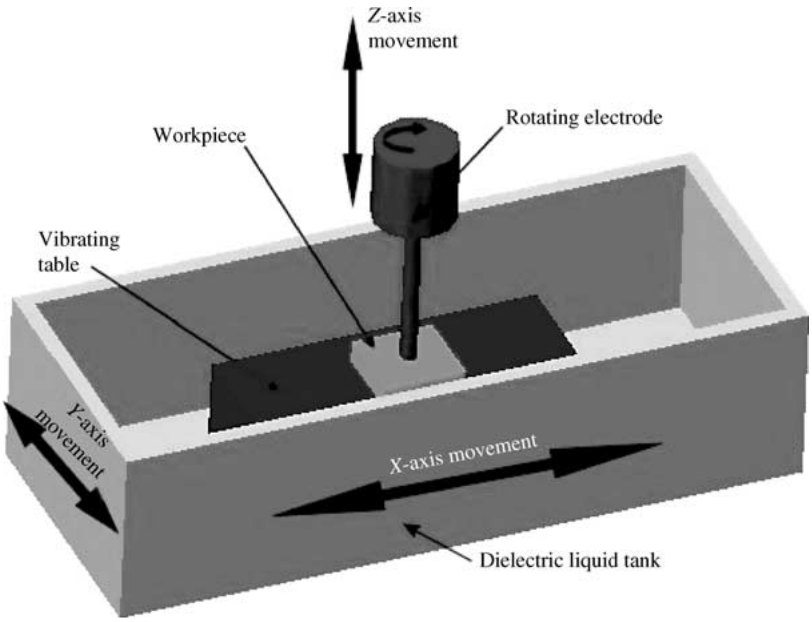

Fig. 1. *Schematic sketch of the experimental setup: workpiece is clamped to the ultrasonic vibrating table immersed in the dielectric liquid tank.*

The efficiency of micro EDM can be improved by the introduction of ultrasound [14]. Ultrasound is a sound wave that has a frequency greater than 20 KHz. It is generated by applying an alternate current to a piezo-electric crystal that is found in the transducer in the sound head. This crystal contracts and expands at the same frequency at which current changes polarity. The sound field generated by this crystal in turn makes the molecules in the sound field vibrate and oscillate. Since solids and liquids consist of molecules held together by elastic forces they behave like rubber bands connecting each molecule to each of its nearest neighbors. If one molecule is set in vibration, then it will cause its immediate neighbors to vibrate, and in turn their neighbors, and so on until the vibration has propagated throughout the entire material. This is the mechanism of energy transmission during ultrasonic vibration. When the EDM electrode is subjected to ultrasonic vibration, the liquid flow behavior improves substantially and the machined surface quality can be improved [15].

3. Experimental Details

The experimental work is conducted using a micro EDM system, MG-ED72W, to machine micro grooves. The experimental setup is schematically shown in Figure 1. Capacitance values 10, 100, 220, and 3300 pF and voltage, ranging from 70 to 110 V, can be applied in the electrical circuit of the micro EDM. Both positive and negative polarities can be used for spark erosion. The machine can be programmed for the positioning increment of 0.1 μm in the *X*-, *Y*- and *Z*-axes. The *X*- and *Y*-axes provide the longitudinal and lateral movement of the work table. The *Z*-axis provides the vertical movement of machine spindle. The positioning range for the respective axes is 200, 50, and 50 mm.

With an additional attachment, the worktable can be ultrasonically vibrated. The amplitude of the vibration can be varied from 0 to 10 μm. Built-in wire grinding unit is used to grind the electrode to the desired dimension. The experimental parameters used in this study are shown in Table 1.

Commercially available titanium alloy (Ti6Al4V) was used as the work material. The compositional details of the work material were obtained by XRD analysis as shown in Figure 2.

The machining was done initially by conventional micro EDM. Then the experiment was repeated by subjecting the workpiece to ultrasonic vibration whose amplitude was gradually varied to values shown in Table 1.

Table 1. *List of process parameters*

Parameter/variable	Value
Work piece	Commercially available titanium alloy (Ti6Al4V)
Tool electrode	Diameter 20 μm tungsten rod
Voltage	90 V
Polarity	Work piece is the cathode and tool electrode is the anode
Capacitance	220 pF
Amplitude of ultrasonic vibration	0, 2, 4, 6, 8, and 10 μm

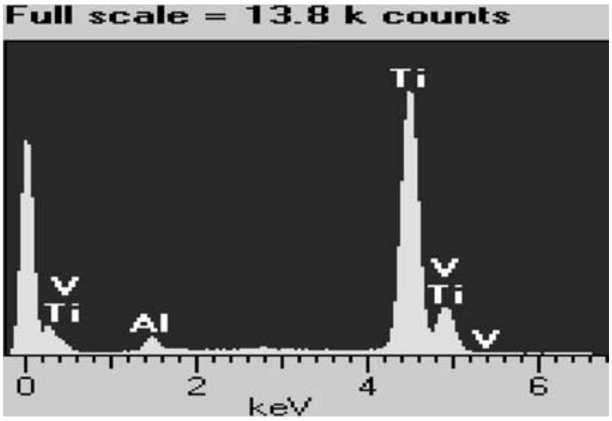

Fig. 2. *The XRD analysis is done to know the details of the composition of the work material which is made of aluminum, vanadium, and titanium.*

4. Results and Discussion

4.1. Fabrication feasibility

In this study the standard tungsten electrode having a diameter of 300 µm was ground to the required size as shown in Figure 3 by using the built-in wire grinding option.

The width of the micro channel depends on the width of the electrode used and also on the sparking gap, which is affected by the machining conditions. Using the precisely made electrode shown in Figure 3, micro channels of width 25 µm were made on titanium alloy. The movement of the electrode during the process of micro channel machining is shown in Figure 4.

The length and the depth of the micro channel can be programmed and computer controlled. By removing the material step-by-step as shown in the Figure 4, a micro channel of required length and depth can be achieved. Scanning electron microscopy (SEM) was used to obtain the image of the micro features with K450 magnification and is shown in Figure 5.

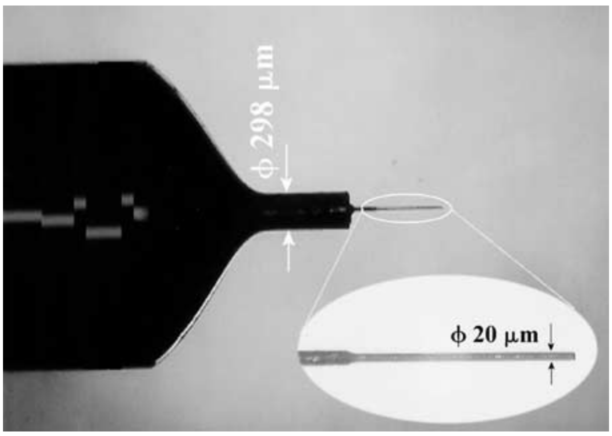

Fig. 3. *Tungsten micro electrode of diameter 20 µm was fabricated by wire grinding the standard 300 µm diameter electrode. Image obtained using OMIS optical microscope.*

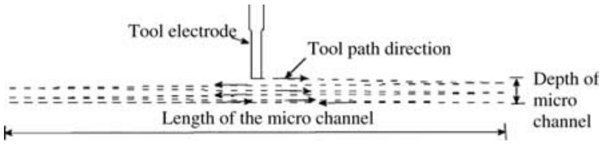

Fig. 4. *Bi-directional tool path movement during channel machining by micro EDM. Arrow shows the direction of the tool movement, which changes alternatively with every pass.*

The total time taken for machining the micro channels is about 4 hours. This includes the time taken for electrode grinding and setting up and referencing of the workpiece and the actual sparking time. This attempt demonstrates that it is feasible to machine micro features as small as 25 µm in few hours time on electrically conductive material using micro EDM.

4.2. *Effect of ultrasonic vibrations on the surface roughness*

In this study the effect of amplitude of the ultrasonic vibration on the surface roughness of the micro grooves made is analyzed. The parameters considered for the study are the arithmetic average height parameter (R_a) and the Ten-point height (R_z). They are explained below.

Arithmetic average height parameter (R_a)**.** This is also known as the center line average (CLA), and is the most universally used roughness parameter for general quality control. It is defined as the average absolute deviation of the roughness irregularities from the mean line over one sampling length. The mathematical

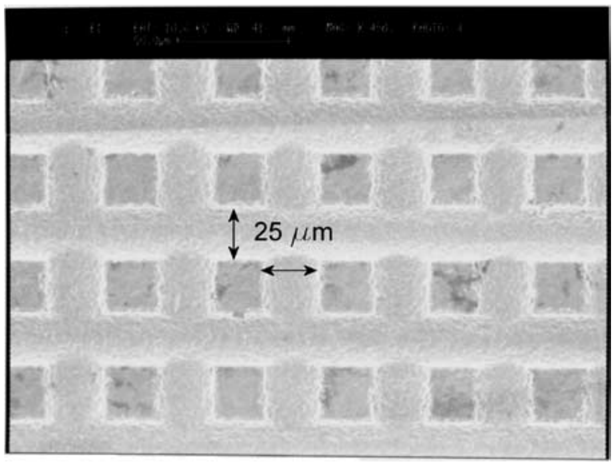

Fig. 5. *SEM image of 25 µm wide micro channels made in Ti6Al4V using micro EDM. Magnification K450.*

definition of the arithmetic average height parameter is given in equation (1).

$$R_a = \frac{1}{l}\int_0^l |y(x)|dx. \quad (1)$$

The digital implementation of the equation (1) is given by

$$R_a = \frac{1}{n}\sum_{i=1}^{n} |y_i|, \quad (2)$$

where n is the number of samples along the assessment length.

Ten-point height **(R_z).** This parameter is more sensitive to occasional high peaks or deep valleys than R_a. The International ISO system defines this parameter as the difference in height between the average of the five highest peaks and the five lowest valleys along the assessment length of the profile. This can be mathematically expressed as shown in equation (3).

$$R_{Z(ISO)} = \frac{1}{n}\left(\sum_{i=1}^{n} p_i - \sum_{i=1}^{n} v_i\right). \quad (3)$$

Non-contact measurement of the surface roughness of the spark-eroded surface is done using Wyko NT 2000 optical profiler. The instrument uses optical phase-shifting (PSI) and vertical scanning interferometry (VSI) for measurement. Since the working surface is relatively coarse, the VSI mode is chosen for the measurement and the results obtained are shown in Figure 6.

Figure 6 shows that with the ultrasonic assisted micro spark erosion machining, the surface roughness values R_z and R_a are below 2.6 and 0.4 μm respectively. These values are well within the recommended R_z and R_a values of 3.4 and 0.4 μm for biological studies like implant abutment [16]. Many bio experiments use specimens having surface roughness in this range, and the present work demonstrates the potential of using micro EDM for making biocompatiable devices for such studies [17–23].

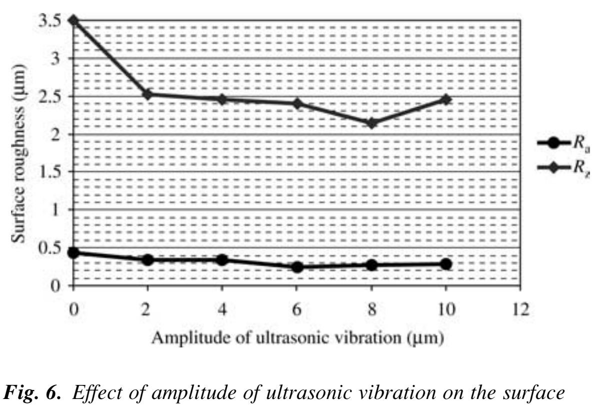

Fig. 6. Effect of amplitude of ultrasonic vibration on the surface roughness of the micro grooves made. Measurement taken in non-contact mode using Wyko NT 2000 optical profiler.

From the graph it is clear that the surface roughness R_a reduces by 19 to 43% and R_z reduces by 28 to 38% when the workpiece is subjected to ultrasonic vibration during the spark erosion. This may be explained in the following manner. During the spark erosion the material removed from workpiece and tool electrode form debris. If the debris is not removed properly, it gets accumulated in the narrow working zone between the tool and workpiece. This leads to the undesirable phenomenon known as arcing. Arcing is an uncontroled sparking due to short-circuiting occurring in the presence of excessive debris. This affects the efficiency of spark erosion and damages the surface, resulting in higher surface roughness. This situation is improved when the workpiece is ultrasonically vibrated. The cavitation effects of ultrasound generate micro bubbles in the narrow gap in tool-workpiece interface and the sudden collapse of these bubbles generate shock waves which facilitate the better removal of debris. Hence the working zone remains clean and the arcing tendency is minimized and smoother surface is obtained.

5. Conclusion

Following conclusions can be drawn from this study of spark erosion machining of micro channels on titanium alloy using the ultrasonic vibration of the workpiece.

1. Micro EDM has been successfully used for the fabrication biocompatible micro device. Feature size as small as 25 μm can be readily achieved.
2. The total fabrication time (including setup and tooling) is about 4 hours in the present work. Hence this method is highly suitable for the rapid fabrication of high precision prototype.
3. As the process does not involve the costly and time-consuming mask preparations, any design changes can be quickly incorporated into the hardware. This is desirable especially in the early stages of the experimental verification of the design.
4. Considerable reduction in the surface roughness (about 20–40%) is achieved when the workpiece is ultrasonically vibrated. The surface roughness achieved is well within the recommended R_z and R_a values of 3.4 and 0.4 μm for biological studies like implant abutment.
5. The small feature size achieved and the surface finish obtained in the present work demonstrate the potential of using micro EDM for making biocompatible devices for bio experiments.

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