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Development of Ultrasonic Pulsation Wire Electrical Discharge Turning Device for Micro/Nano Medical Part Manufacturing

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ABSTRACT

Micro/Nano manufacturing has re-engineered the medical devices technology to component miniaturization. Despite of numerous technical challenges, tremendous development of micro/nano medical devices continue to grow. Wire electrical discharge turning (WEDT) is a hybrid process that combines two mechanics of cutting i.e. wire electrical discharge and workpiece rotation. Its 'free of cutting force" property made it one of the desirable techniques for manufacturing intricate micro/nano cylindrical components. Despite its capability for fabricating micro/nano-size components, the main concern was its unstable spark discharge energy that resulted in poor machined surface quality. Unlike a normal wire-EDM process, the rotating workpiece alters the mechanic of material removal process causing unstable energy density and high pulse intensity. In order to solve the discrepancy, one of the possible techniques is to incorporate an ultrasonic pulsation frequency which has been proven to increase the machined surface quality on similar die sink EDM erosion process. Hence, based on the proven concept, this paper proposes a novel strategy to control the spark discharge energy by incorporating the ultrasonic pulsation in the WEDT process with the aim to enhance the machined surface quality. In the paper, the development of an ultrasonic pulsation rotary wire electrical discharge machining device for micro/nano medical part manufacturing aiming to improve the surface integrity of machined parts, i.e. surface roughness and sub-surface damage are presented. Experimental trials on machining titanium alloy were conducted to evaluate the capability of the proposed rotary ultrasonic device in fabricating micro/nano size part. From experimental results, it was found that the new rotary ultrasonic device was capable of machining complex micro/nano geometric features. In addition, the improvement on large L/D machining ratio under single pass ultrasonic cutting condition was also achieved.

Keywords: Precision Machining, Micro/Nano Manufacturing, Ultrasonic Assisted Wire Electrical Discharge Turning.

1. INTRODUCTION

In most of the micro/nano-machining processes, the cutting force influences the mechanics of material removal mechanism which limits the machinable size due to the physical contact between tool and workpiece. Due to the high stiffness of the micro part feature, deformation is more likely to occur in the machining process which results in dimensional surface errors, break and poor surface quality [1]. In the medical field, most of the devices are made from difficult-to-cut materials such titanium alloys and stainless steel [2]. Some of those devices such micro-probe, micro-cannula and grasper (Figure 1) possess high aspect ratio which is 0.1 to 0.5 mm in

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diameter but up to 60 mm in length. This length scale integration limits the application of traditional machining process as well as the application of complicated geometries such as the laparoscopic grasper used in robot-assisted minimally invasive surgery shown in Figure 2.

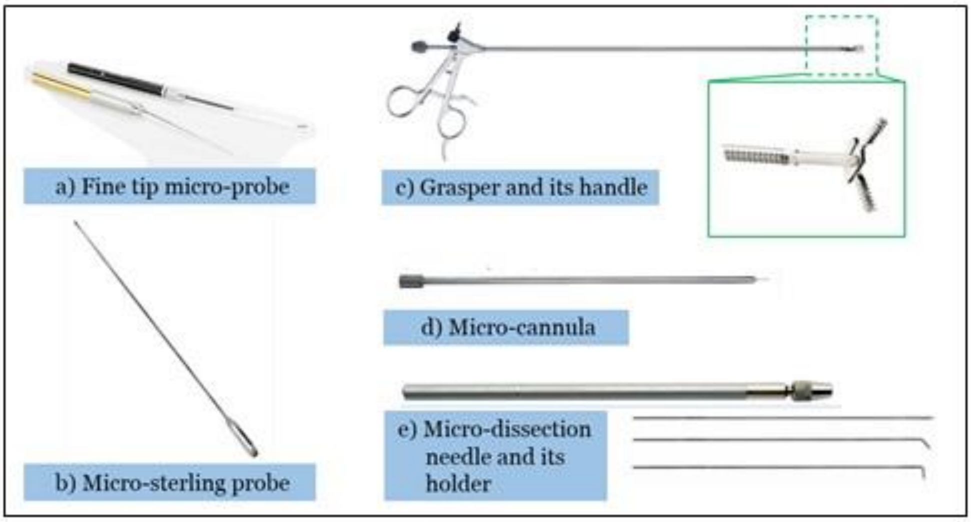


Figure 1. Micro surgical instrument.

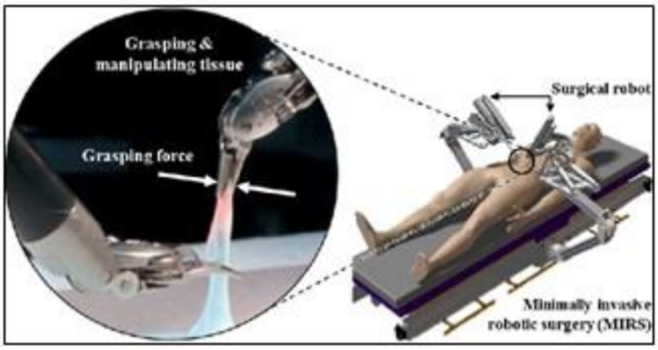


Figure 2. Complex surgical grasper tool shape used to grasp and manipulate tissue during robot-assisted minimally invasive surgery (RMIS).

Wire electrical discharge turning (WEDT) became an alternative machining method to counter the drawbacks in micro-machining of difficult-to-cut materials. WEDT provides the capability in fabricating a variety of complex geometrical features of macro-micro dimension without limiting the parts aspect ratio by a single setup. Moreover, the capability of this process in performing contour machining for profile shapes has been an eye-opener for the manufacturing industry to accept its usage. Figure 3 shows the machining capability of WEDT summarized according to literature and industrial practice.

However, one of its limitation is the difficulty in achieving excellent surface integrity. Surface integrity is the surface condition of a workpiece after being modified by a manufacturing process; it includes surface roughness, metallurgical microstructure and thermally processed surface layers. Low surface roughness is required in medical device manufacturing. For example, in artificial heart valve applications, a rough surface can cause turbulence in the blood, which in turn may damage the integrity of red cells, cause the adhesion of bacteria, and result in blood coagulation and clots [3]. In term of bio-burden aspect (Figure 4), unclean/dirty surgical instruments can be a consequence of rough surface and surface defects generated in the manufacturing processes, which make the residence of organic debris on the surface easier. Moreover, the imprecise movements of micro forceps due to fatigue and micro cracks often may result in tissue damage as well as sight-threatening [4].

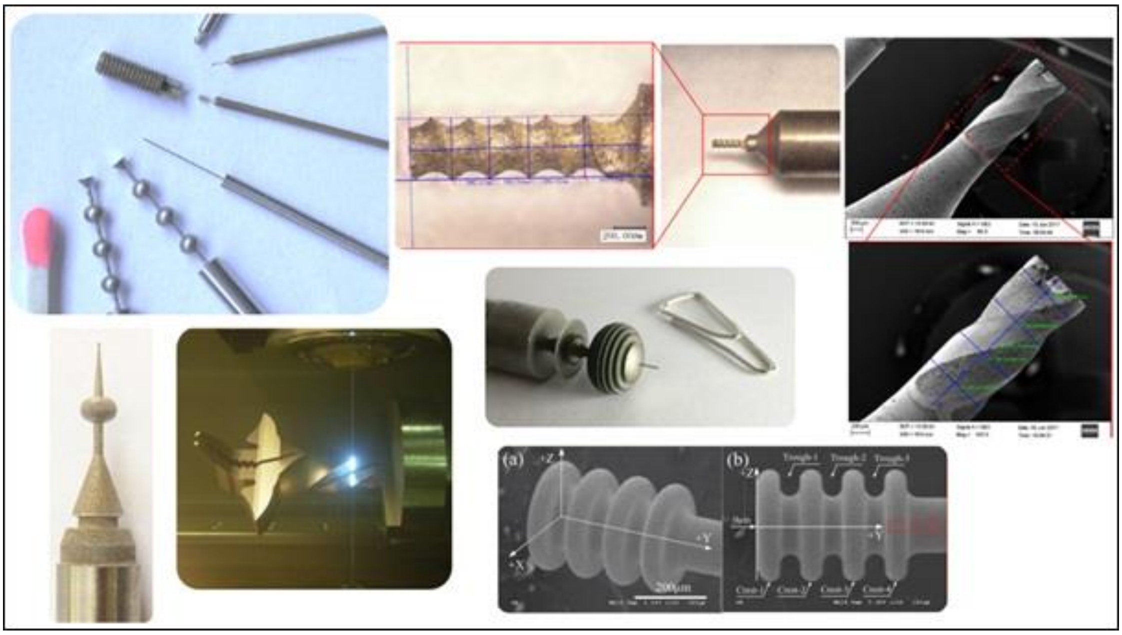


Figure 3. Macro-micro components made by WEDT such as micro bellow core-mould, micro-mill tool, micro fins, micro-tip forceps and etc.

Figure 4. Bioburden on the surgical devices may infect patients who undergo surgery.

It is well-known that surface finish and micro-crack can influence the fatigue life of materials strongly [5]. During high-cycle fatigue of many materials, the majority of cyclic lifetime (up to 90%) is consumed during the creation of an initial flaw, or sub-critical crack. The presence of microcracks in brittle, thermally-processed surface layers – typical of spark erosion processing – creates conditions ripe for pre-existing flaws to exist.

In WEDT, the alteration of the spark energy due to the rotating workpiece leads to poor flushing effects which affect the metallurgical properties under the machined surface [4]. This is because the static discharge channels cannot be maintained over long “pulse on” time, such as rotating workpieces where the discharge channel is interrupted by rotary motion. Thus, the discharge energy becomes fluctuated and unstable. In this state, more arcs and arc region occur compared with when the workpiece is in static condition such as in wire electrical discharge machining (WEDM) due to the reduction of spark gap during erosion process. Figure 5 shows the comparison of pulse waveform between the rotating workpiece and the static workpiece in this process. Due to this kind of uncontrollable pulse (arc and short pulse), the surface integrity will deteriorate. Lots ~~of~~ micro-cracks (Figure 6 and Figure 7) in the recast layer of the sub-surface region will be found, thus the mechanical properties such as fatigue strength and service life are weakened.

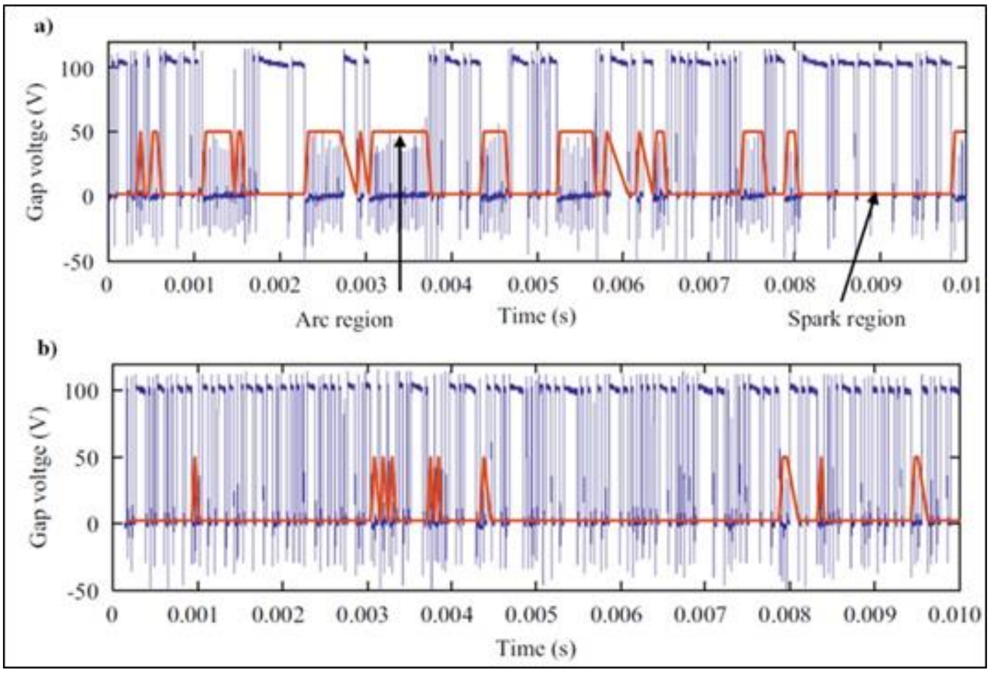


Figure 5. Comparison of pulse trains for a) Rotating workpiece (WEDT) and b) Static workpiece (WEDM) [6].

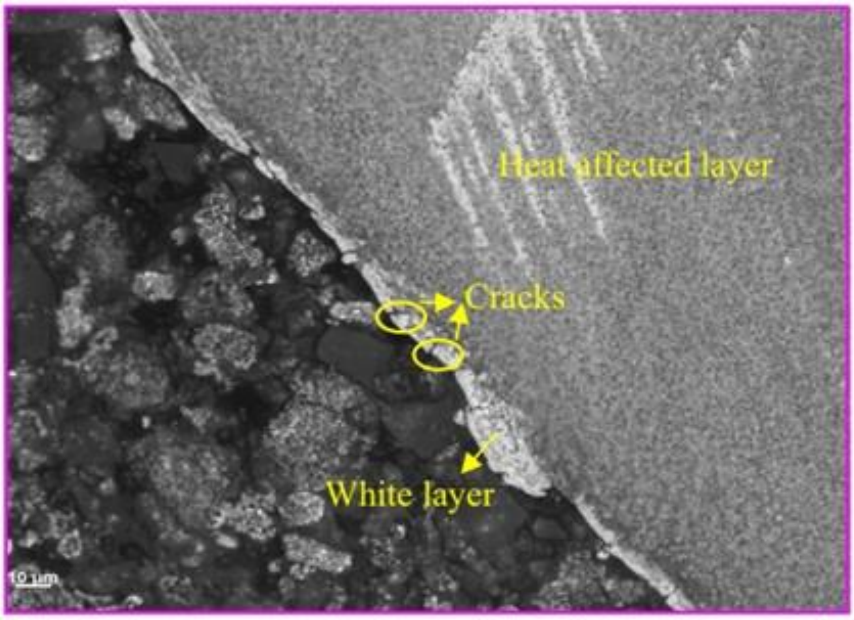


Figure 6. The occurrences of thermally-affected layer on parts which reduce the service life [7].

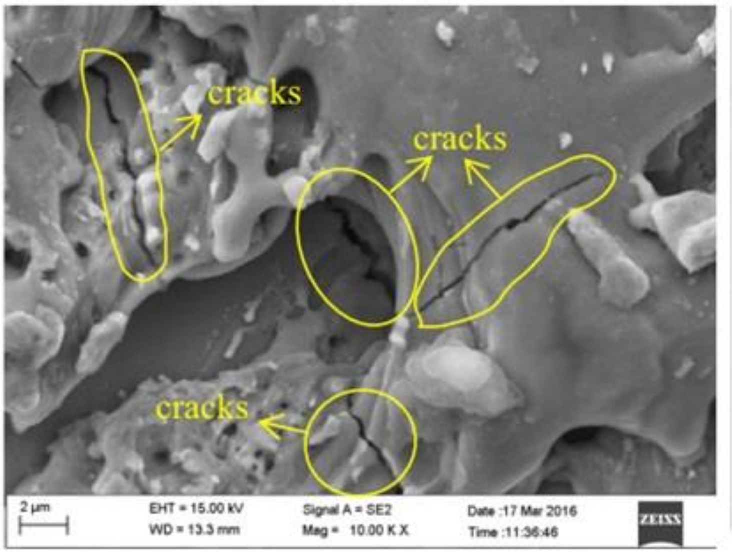


Figure 7. The sub-surface micro cracks [8].

Based on the analysis of deficiencies, an effective approach to solving these issues is to incorporate ultrasonic vibration in the spark erosion process by transmitting the ultrasonic pulsation to the machining zone. The vibration can not only stabilize the pulse waveform but also improve the flushing condition in the discharging gap [9]. Consequently, it is reasonable to anticipate that by applying the assisting ultrasonic pulsation to the machining zone in terms of flushing, cavitation, reduced arcing and open pulse circuit and improved surface integrity of the final part, can be achieved [10, 11].

In this paper, the development of an ultrasonic pulsation rotary device for wire electrical discharge machining were presented. It aims to improve the length to diameter ratio as well as the surface integrity of the machined part, i.e. surface roughness for micro/nano medical part manufacturing.

2. DESIGN AND DEVELOPMENT OF ULTRASONIC ROTARY MECHANISM

The ultrasonic rotary axis mechanism was developed to work on commercially available WEDM machine. The design of rotary axis mechanism was proposed and illustrated with computer-aided design (CAD) model including the details of the subparts. Most of the parts and subparts were selected based on available existing commercialized parts based on the advantage of ease of part replacement of tear and wear. The mechanical parts, hardware, software namely rotary spindle and speed controller are built, integrated and assembled together that will be described in detail at the later sections.

There are three main components needed in developing the rotary unit as shown in Figure 8, where the first main component is the rotating clamping system that holds the workpieces. The consideration of this component is that it should have high accuracy to deliver rotational motion for micro-machining practise. Then, it should allow the flow of an electrical current to the workpieces to form spark erosion. The second main component is the way to motorize the clamping system with variable speed. The third component that should be considered at the design stage is the approach to attach all the other components for ease of installation and prevent from damage by wet environment, back current and corrosion. Other design consideration is to barricade the bearing from damage by the interference of machine polarities. According to literature surveys, among all the developed rotary unit, there is no rotary unit that is capable to fabricate blending of macro-micro part components with surface profile shapes.

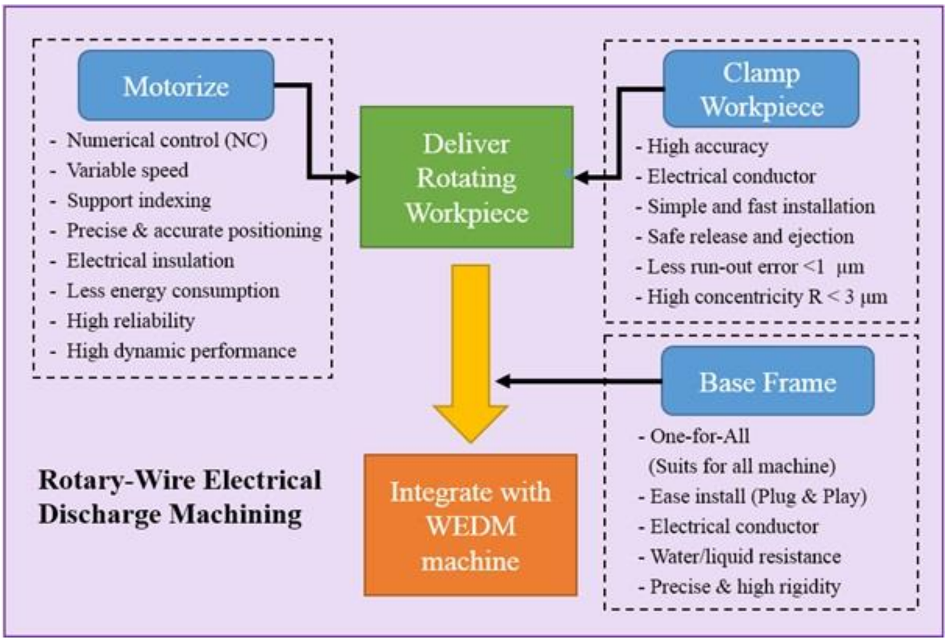


Figure 8. Components involved in the development of ultrasonic WEDT.

2.1 Ultrasonic Rotary Spindle and Housing

The ultrasonic rotary spindle component is the most important consideration that needs to be taken in the development since it is the main component to perform the ultrasonic WEDM process. The selection of inappropriate shaft spindle and clamping system may cause inaccuracy and out of the component tolerances. The main factor that contributes to the accuracy is run-out error. The selection and assembly of the clamping system should reduce and minimize the run-out error. In this present study, an in-house rotary axis mechanism is developed using ultrasonic tools, rotary spindle and housing that comprises of eight components that is integrated to perform as WEDT rotary axis mechanism. Figure 9 and Figure 10 show the pre-assembly of ultrasonic rotary spindle on a housing and the ultrasonic tool actuator respectively.

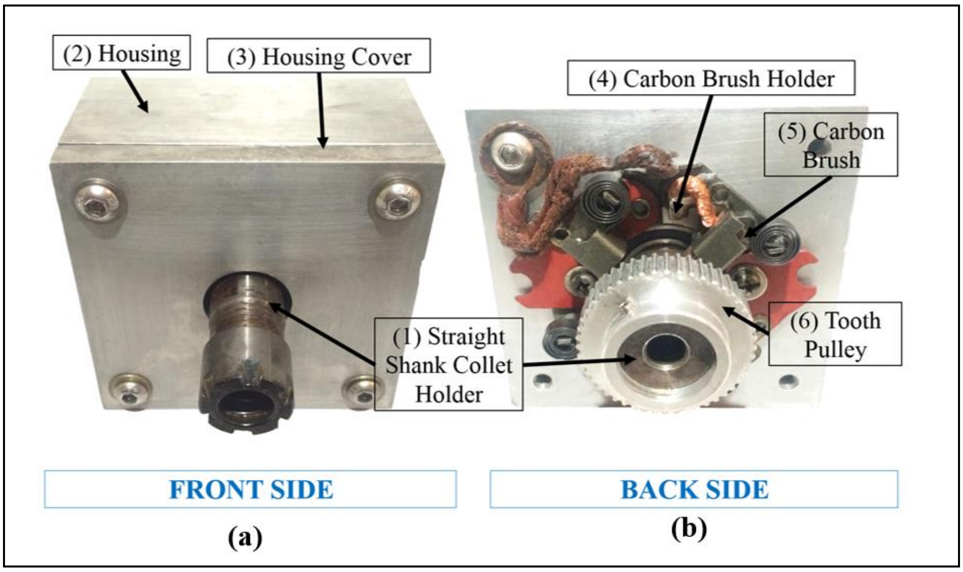


Figure 9. Pre-assembly rotary spindle and housing (a) Front side (b) Back side.

Figure 10. Ultrasonic tool actuator.

All the components selected were based on concept, theories and practices that have been used by the previous literature. In addition, the selected components also were common parts which are commercialized in market except housing and housing cover. These components are easy to be replaced, especially for wear and tear components (carbon brush and ceramic bearing). Table 1**Error! Reference source not found.** shows the details of the components which were used for the ultrasonic rotary spindle development. Table 2 describes the function of each of the components to the rotary axis mechanism.

Table 1 Name, dimension, specification details and material of the components

No.	Component	Dimension (mm)	Specification	Material
1	Ultrasonic Tool Actuator	46x174 (D x L)	**Brand:** KLI Technology **Frequency:** 20-27 kHz **Amplitude:** 1-5 μm	**Body**: Stainless steel
2	Straight Shank Collet Holder	20x100 (D x L)	**Brand:** Master **Collet:** ER16 Metric **Clamp Diameter:** 1-10 mm **Run-out Tolerance:** 15 μm (DIN6499B)	1065 Grade Carbon Steel
3	Housing	90x90x44.8 (W x L x T)	A pair of counterbored holes	Aluminium
4	Housing Cover	90x90x8.5 (W x L x T)	One counterbored holes	Aluminium
5	Carbon Brush Holder	59x59x14 (W x L x T)	**Spring Type:** Coil **Maximum Quantity:** 4 units carbon brushes	Copper and brass
6	Carbon Brush	12x21x8 (W x L x T)	**Brand**: Nippon, Japan	Graphite
7	Tooth Pulley	27x16 (D x L) Hub Diameter 26	**Brand:** RS **Teeth:** 48 **Pitch:** 2.5 mm	Aluminium
8	Radial Oil Seal	20x47x7 (ID x OD x T)	Including Garter Spring	Rubber
9	Ceramic Bearing	20x32x7 (ID x OD x T)	**Brand:** Kanzen Roulement, France **Precision Levels:** ISO 5/ ABEC 5 (ABMA, n.d.) **Type:** Deep Groove Radial Ball Bearing **Closures:** Double sealed	**Races:** 440C Stainless Steel **Balls:** Si_3N_4 G5 diamond polished **Seals:** Rubber

	Lubrication: Self Lubricated (Grease)

Table 2 Components and their functions in rotary axis mechanism

No.	Component	Function
1	Ultrasonic Tool Actuator	• Transmit ultrasonic frequency and amplitude using piezoelectric mechanism. • Integrate with ultrasonic generator and controller
2	Straight Shank Collet Holder	• Work as spindle shaft in rotary axis mechanism • Transmit power, torque and motion from one location to the workpieces • Minimize the run-out error from the joining between shaft and chuck or others clamping devices [7].
3	Housing	• Locates a pair ceramic bearing at centre of the housing for holding the spindle shaft
4	Housing Cover	• Place a radial oil seal
5	Carbon Brush Holder	• Hold and maintain constant contact forces on carbon brushes to spindle shaft [7]
6	Carbon Brush	• Deliver or collect electrical current from a rotating to static components, or vice versa [12]
7	Tooth Pulley and Tooth Belt	• Receives motion from timing belt which is transmitted by another pulley and driven by electrical motor [8] • Provide uniform flow of motions [13]
8	Radial Oil Seal	• Seals around a rotating spindle shaft and housing from dielectric fluid and eroded particles (debris) that capable to enter the gaps around the bearing and assembled components during EDM process
9	Ceramic Bearing	• Support, ensure stability and provide frictionless rotation for spindle shaft • Locate and hold a spindle shaft at centre of the housing • Prevent the electrical discharge occurs between the gap on steel bearing [12] • Prevent from back current that will damage the motor [7]

2.2 Speed Controller

In developing the speed controller, the idea is to employ the pulse-width-modulation (PWM) method. PWM uses variable duty factors that is particularly suitable for speed control applications, in this case, the rotational spindle speed in the rotary axis mechanism. Therefore, all of the electronic parts that are used in this study are based on the development of speed controller system by using PWM technique.

Figure 11 shows the connection between electronic components which consist of a microcontroller board, a motor driver and a voltage regulator. According to Figure 10, the input power source for the whole system is a 24V power supply with 1 ampere current. However, since only the brushed DC motor is driven by 24V, other components are operated by the voltage of less than 12V, the voltage supplied by the power source is reduced to 12V by a voltage regulator to drive the microcontroller board (SK40C). MD10C is preferred to drive the DC motor because it offers both locked-antiphase and sign-magnitude PWM signals. Other than that, this motor driver supports a wide range of voltage that suits the particular motor in this research work. More precisely, the motor driver has four input and two output pins with one grounding pin. The first two input pins are connected to the power supply and the two output pins are connected to the DC motor. The other two input pins are the PWM pin and the direction pin. These pins with one grounding pin are connected to the SK40C and they control the amount and direction of the current that goes into the DC motor.

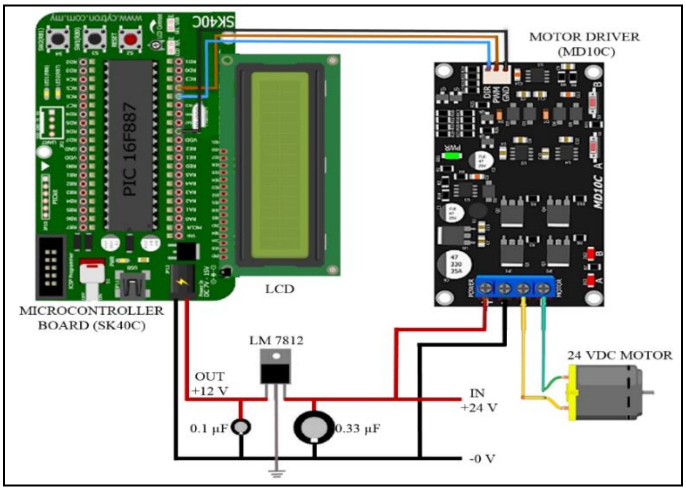


Figure 11. The speed controller integration of SK40C, MD10C, voltage regulator and DC motor.

2.3 Final Assembly

In the final assembly, all the parts are installed together as shown in Figure **11** to **Error! Reference source not found.**. The set of DC motor is mounted to the base frame as mentioned in the previous section. Then, the complete pre-assembly set of housing is also mounted to the base frame. After that, the tooth belts are fitted on tooth pulleys at the DC motor and shaft spindle. The tension bolt is used to obtain suitable tension on the tooth belt. Tooth pulleys and belt are used to simplify the transfer of the rotational motion from the powered pulley on a DC motor to one driven pulley at spindle shaft. The straight shank collet holder is used with the ER16M adapter as a clamping device and serves as a spindle shaft. The range diameter that is allowed for this adapter is 1 to 10 mm. In this study, the range adapter of diameter size was about 9 mm.

Spindle shaft is placed on a pair of ceramic bearings at both ends, and the ceramic bearing is press fitted to the housing. The ceramic bearings are deep groove Si_3N_4 ball bearings with stainless steel inner and outer races, rubber sealed with ABEC grade 5 is used to prevent the electrical discharge to occur between the gaps on the ball bearing. At the outer of the housing, radial oil seal is placed to avoid the excess melted material (debris) during the erosion process as well as to prevent de-ionized water from entering the bearing races. Since the EDM process requires connectivity between terminals, the rotating workpieces require link to the WEDM machine worktable. Therefore, a pair of carbon brush, which is a slid contact to the spindle shaft and the carbon brush, is connected to the housing which has direct contact to the WEDM machine worktable. Carbon brushes are used to transmit electrical current from a static to a rotating spindle shaft. It is fixed on the back of the housing by using the carbon brush holder. The workpiece is clamped on the spindle shaft by a collet adapter and locked by the collet nut. In this study, the rotation direction of the spindle shaft is designed similar to the direction of the DC motor with the same amount of ratio. Finally, the rotary axis mechanism is mounted on the WEDM machine worktable and aligned with its X or Y axis.

The speed controller and ultrasonic generator were energized by the plug-in 24V adapter and was switched on. Then, the connection cable is inserted to the female jack that is linked to the motor driver (MD10C). During the spark erosion process, the rotating workpiece is interrupted by continuous perpendicular electrode wire that is replenished to replace the new electrode wire surface that is available for next spark. By applying the rotational motion, the un-machined portion of the workpiece surface is replaced by machined portion, and vice versa.

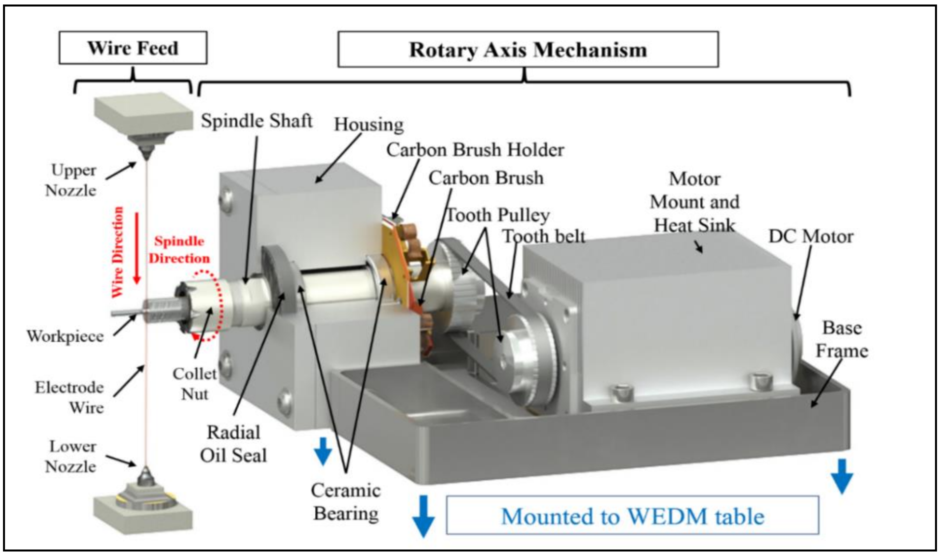


Figure 11. CAD design of final assembly of rotary axis mechanism for ultrasonic WEDT.

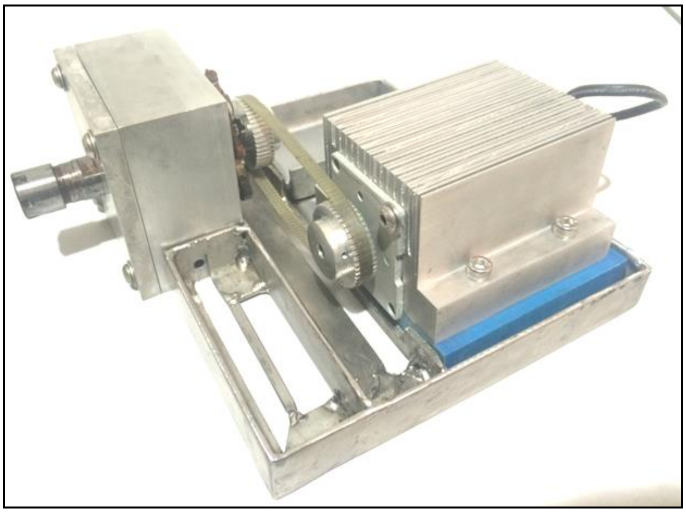


Figure 12. The actual final assembly of rotary axis mechanism for ultrasonic WEDT.

3. RESULTS AND DISCUSSION

Experimental trials on titanium alloy were conducted to evaluate the capability of the developed rotary ultrasonic device in fabricating micro/nano size part. The first test is to evaluate the range of rotational spindle speed. The allowable rotational spindle speed is 50 to 3000 rev/min which is measured by a Tachometer (

Figure **13**). In order to obtain the bearing stability, the rotation of spindle was evaluated in terms of the dynamic run-out as indicated in

Figure **14**. The maximum run-out error produced was as big as 9 µm when the spindle rotates at 2100 rev/min and the minimum run-out error that was able to achieve when spindle rotates at 50 rev/min was as small as 6 µm. By increasing the spindle speed, the run-out dramatically increases, but it slightly decreases at the maximum spindle speed.

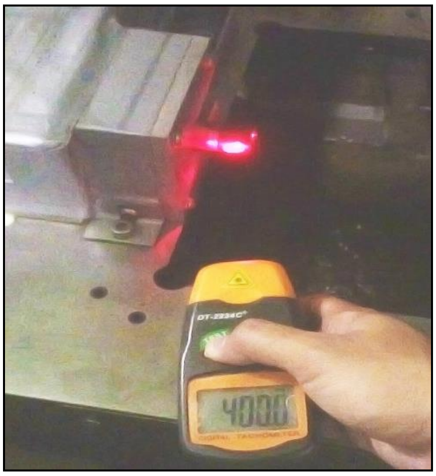


Figure 13. Rotation of spindle is measured by laser type Tachometer.

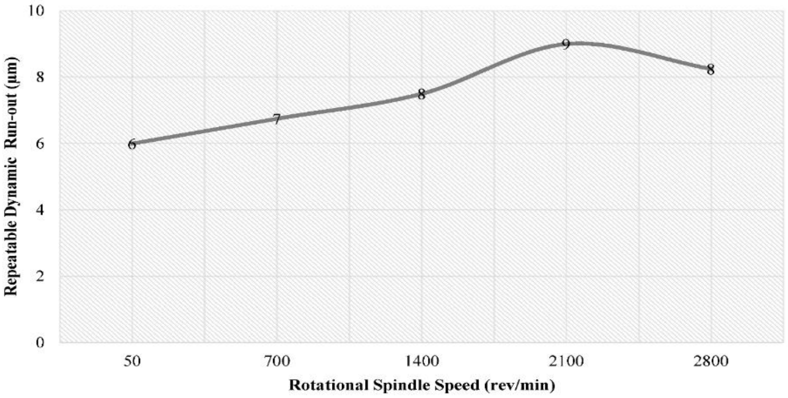
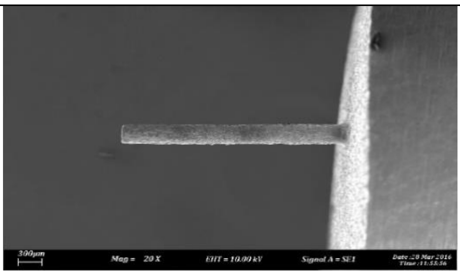
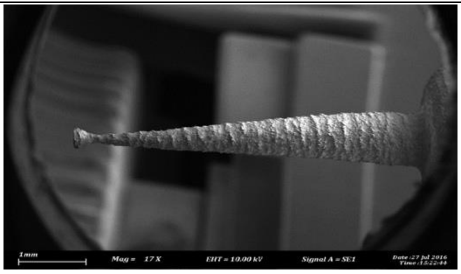
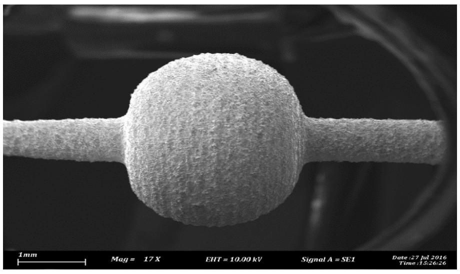
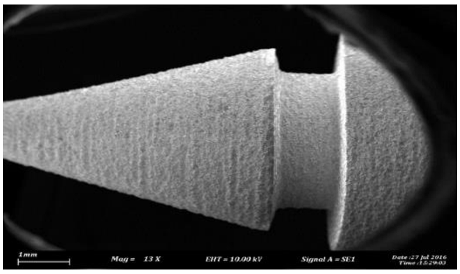
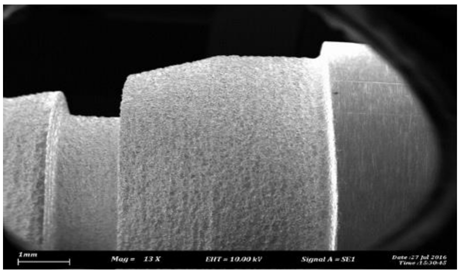


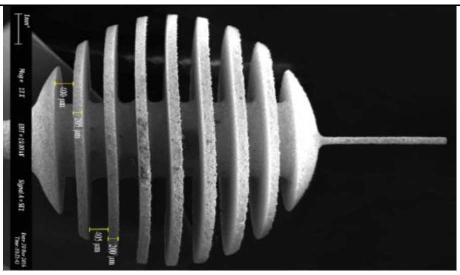
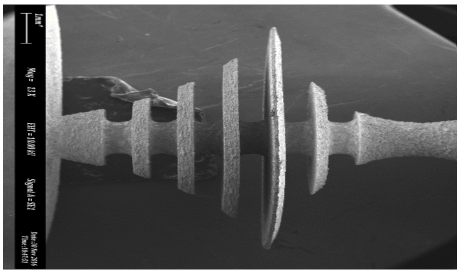
Figure 14. Results of the repeatable dynamic run-out of the spindle with varying rotational spindle speeds.

The performance of the developed ultrasonic rotary axis mechanism was evaluated for machining micro-cylindrical components. The designs that have been considered are straight turning with maximum achievable diameter followed by contouring turning with blending of macro and micro dimension. **Error! Reference source not found.** shows the geometry and shape that is fabricated by this ultrasonic rotary axis mechanism assisted by WEDM machine and the macro-micrograph of the parts that are obtained through the scanning electron microscope (SEM).

Table 3 Rotary axis mechanism fabrication capabilities of shape and design

Fabricated Components	Descriptions
	Employs one pass of straight turning operation to form cylindrical shaft with maximum achievable diameter approximately 0.2 mm and machining length as much as 200 mm. The aspect ratio (Length/Diameter) is as much as 1000.

	
   	Employs the operation of a single pass contour turning to produce four types of shapes which are dovetail, cone, ellipse and groove. The micro size dovetail shape is successfully fabricated. More specifically, a bottom (neck) diameter of 163 µm and top diameter 372 µm. During the WEDT process, the discharged energy generates extreme temperatures causing the materials to melt and vaporize. For every single discharge, a crater was formed on the machined surface that changed the machined surface topography by effects of various process parameters. It was observed from the SEM micrographs of WEDT surface that contains globules of debris, that there were different sizes of craters and micro-voids. The surface topography of WEDT almost has similar characteristic with surface topography of normal WEDM, but WEDT machined surface contains elongated craters because of the effect of rotating workpiece that makes the plasma arc column to simply slide over the machined workpiece and elongate the craters. During machining, some of the molten material produced by the discharge energy were flushed away by the deionized water but the remaining molten material re-solidified to form globules of debris as seen depicted in Figures 15-16. It can be observed that, the occurrences of micro-void are caused by the bubbling gas expelled from the molten material during solidification due to the effects of the cooling rate by de-ionized water.

 	Employs the operation of a single pass contour turning and slitting operations of micro straight shaft and fins to the macro dimension of ellipse, cone and hour glass shape. Dimension of micro fins and straight shaft of 200 µm and the average of slitting kerf width of 400 µm. The gap spacing between the fins can be controlled based on the summation of several parameters namely wire diameter, wire tension and spark discharge energy. Employing ultrasonic pulsation to the machining zone has created additional kinematic part movement that improved the debris flushing process, cavitation, reduced arcing and open pulses circuit which substantially improves the surface integrity of the final part.

Further evaluation on surface condition of machined surface was performed using SEM and IFM. Figure 15 and Figure 16 show the machined surface on lateral surface of cylindrical parts for the non-present and present of ultrasonic pulsation respectively. It was found that, the occurrence of bumpy rough surface roughness in the specimen produced by non-present ultrasonic pulsation as compared to much smoother and better surface roughness in the specimen produced by the present of ultrasonic pulsation. During spark erosion at high voltage interaction either in high or low wire tension leads to destroying the even surface texture by violent sparks produced by large discharged energy during pulse on time. The nature of voltage brings the potential difference of electric that is amplified together with electric current to the creation of discharged energy. The huge discharged energy will form strong sparks penetrating to the machined surface and subsequently resulting in deeper craters. The ultrasonic pulsation to the machining zone generated additional kinematic movement of part that improved the debris flushing process and reduced arcing and open pulses circuit, and substantially improved the surface integrity of the final part.

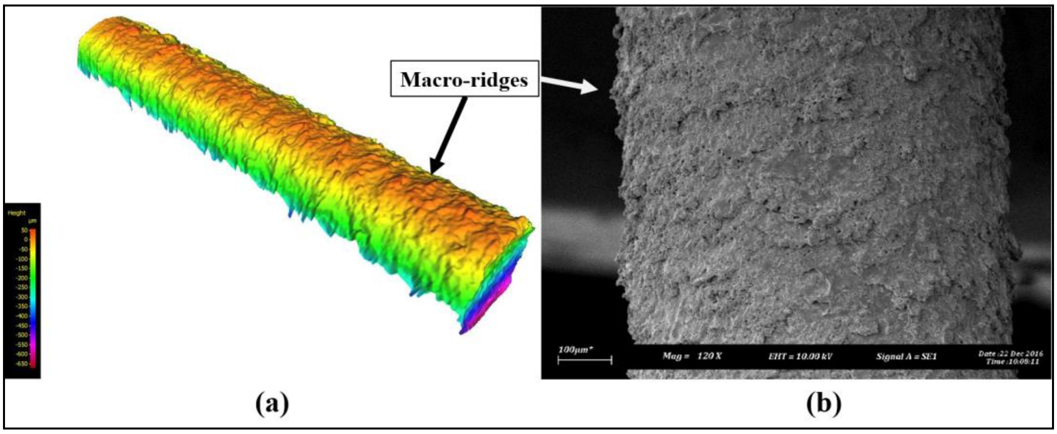


Figure 15. a) IFM micrograph b) SEM micrograph of non-present ultrasonic pulsation WEDT machined surface (Ra: 4.634 µm).

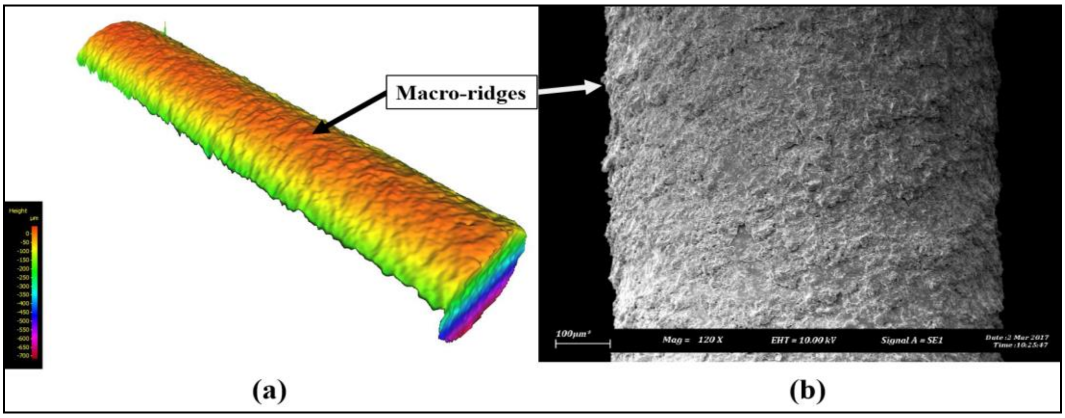


Figure 16. a) IFM micrograph b) SEM micrograph of ultrasonic pulsation WEDT machined surface (Ra: 2.377 µm).

4. CONCLUSION

The ultrasonic pulsation rotary wire electrical discharge turning device developed in the paper is capable of machining a variety of complex micro dimension geometries. The improvement on large L/D machining ratio with a single pass cutting condition were also observed. Introducing ultrasonic pulsation to the machined zone has significantly improved the surface integrity of the final part. The following conclusions can be drawn:

1. The ultrasonic pulsation has created additional kinematic part movement that improved the debris flushing process, cavitation, reduced arcing and open pulses circuit which substantially improves the surface integrity of the final part.
2. The surface topography of WEDT almost has similar characteristic with surface topography of normal WEDM, but WEDT machined surface contains elongated craters because the effect of rotating workpiece makes the plasma arc column to simply slide over the machined workpiece and elongate the craters.

Further investigation on the observation of cutting mechanic by ultrasonic pulsation are still needed. The machining technique proposed in this paper provides the fundamental knowledge for the enhancement of micro/nano size component manufacturing.

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REFERENCES

[1] Zhang, Z., Huang, H., Ming, W., Xu, Z., Huang, Y., & Zhang, G., “Study on Machining Characteristics of WEDM with Ultrasonic Vibration and Magnetic Field Assisted Techniques”, Journal of Materials Processing Technology **234** (2016) 342–352.

[2] Amran M., Izamshah R., Hadzley M., Shahir M., Amri M., Sanusi M., Hilmi H., “The Effect of Binder on Mechanical Properties of Kenaf Fibre/Polypropylene Composites Using Full Factorial Method”, Applied Mechanics and Materials **695** (2015) 709–712.

[3] Jackson, M. J. & Ahmed, "Surface engineered surgical tools and medical devices". Springer Science & Business Media, (2007).

[4] Karaçalı, Ö., "Fatigue Analysis of Ti-55 Alloy Material for Multifunctional Surgical Instruments," in Medical Engineering. Acta Physica Polonica A **127**, 4 (2015) 1199-1201.

[5] M. Amran, S. Laily, H. I. K. Nor, N. I. S. Hussein, M. R. Muhamad, B. Manshoor, M. A. Lajis, R. Izamshah, M. Hadzley, R. S. Taufik, "The effect of EDM die-sinking parameters on material characteristic for aluminium composite using tungsten copper electrode," Applied Mechanics Materials **465** (2013) 1214-1218.

[6] Kumar, A., Kumar, V., & Kumar, J., "Surface Crack Density and Recast Layer Thickness Analysis in WEDM Process through Response Surface Methodology," Machining Science and Technology **20**, 2 (2016) 201–230.

[7] Janardhan, V., & Samuel, G. L., "Pulse Train Data Analysis to Investigate the Effect of Machining Parameters on the Performance of Wire Electro Discharge Turning (WEDT) Process," International Journal of Machine Tools and Manufacture **50**, 9 (2010) 775–788.

[8] Sun, Y., & Gong, Y., "Experimental Study on the Microelectrodes Fabrication Using Low Speed Wire Electrical Discharge Turning (LS-WEDT) Combined with Multiple Cutting Strategy," Journal of Materials Processing Technology **250** (2017) 121–131.

[9] Sun, Y., Gong, Y., Cheng, J., & Cai, M., "Experimental Investigation on Carbon Steel Micro-Rod Machining by Low Speed Wire Electrical Discharge Turning," Materials and Manufacturing Processes **33**, 6 (2018) 597-605.

[10] Kumar, S., Wu, C. S., Padhy, G. K., & Ding, W., "Application of Ultrasonic Vibrations in Welding and Metal Processing: A Status Review," Journal of Manufacturing Processes **26** (2017) 295–322.

[11] Izamshah, R., Akmal, M., Kasim, M., Sued, M., Sundi, S., & Amran, M., "Parametric Study on Parameter Effects in Hybrid Micro Wire Electrical Discharge Turning," Journal of Advanced Manufacturing Technology (JAMT) **12**,1 (2018) 1-12.

[12] Qu, J., Shih, "Development of the cylindrical wire electrical discharge machining process. Part 1: Concept, Design and material removal rate," J. Manuf. Sci. Eng. **124**, 3 (2002) 702-707.

[13] Gohil, V., & Puri, Y.M., "Statistical Analysis of Material Removal Rate and Surface Roughness in Electrical Discharge Turning of Titanium Alloy (Ti-6Al-4V)," Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering **232**, 9 (2016) 1603-1614.