STATISTICAL EVALUATION ON THE EFFECTS OF ROTATION SPEED IN HYBRID MICRO WIRE ELECTRICAL DISCHARGE TURNING

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ABSTRACT: Demand for micro parts fabrication are steadily increase in today's manufacturing technology. Conversely, the traditional manufacturing process through re-sizing and scaling down the machine tools and equipment will affect the component accuracy especially for small difficult-to-machine materials. For that reason, in this study an electrical spark erosion process is adopted to deal with the discrepancy for micro size components manufacturing. This process is synonym with the name of wire electrical discharged turning (WEDT) which incorporates a turning process of rotating workpiece to continuous travelling electrode wire in electrical discharged conditions produced by wire electrical discharge machine. However, incorporating wire EDM to remove material in symmetrical cylindrical shape component causing several challenges especially with regards to the process stability. One of the most important factors that will effect on the WEDT machining performances is the rotational spindle speed. Therefore, knowledge and understanding on the effects of WEDT rotation speed towards part performances namely surface roughness (Ra) and material removal rate (MRR) are necessitate for the success of machining. Based on the experimental results, it was found that increasing rotational spindle speed does not improve MRR. In contrast, by employing high spindle speed capable to produce fine surface roughness on part machined surface. It revealed that an increment in workpiece circumferential length causing an augmentation cumulative of spark region. This phenomenon has increased the energy intensity per unit length as the number of arc regions are increased.

KEYWORDS: *WEDT; Precision Machining; Rotational Spindle Speed*

1.0 INTRODUCTION

Nowadays, complex geometrical micro-size component and instruments has gained great attention particularly in medical and microelectronic sectors [1]. In medical field, the high rate of patient acceptance in minimally invasive surgery and costly treatment lead to the miniaturization in medical devices [2]. Apart from that, advancement of micro inductive sensors and microelectronic components has become the key that drive the micro manufacturing market [3-4]. Emergence of both areas has created a niche market for greater precision, intricate shape and accurate component that became challenges to the existing micro manufacturing capability and technology [5]. Figure 1 illustrates the example of the miniaturized components in several of applications that depends upon micro-manufacturing.

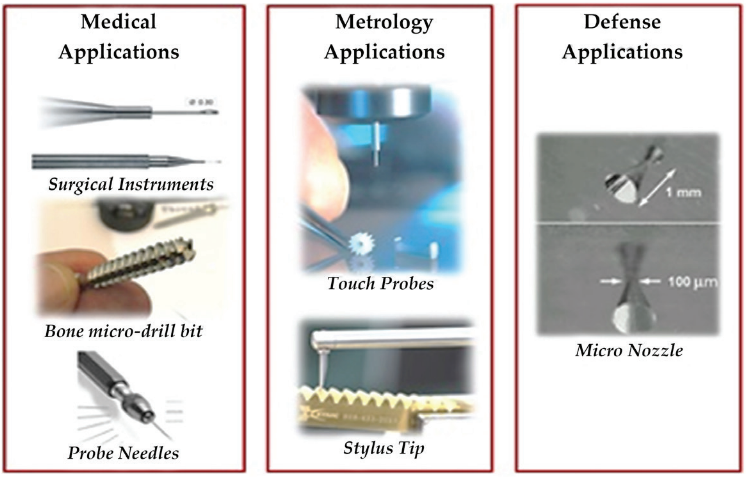

Figure 1: Example of miniaturized components in medical, metrology and defense applications

The evolving of micro parts manufacturing has steadily causing the development of dedicated machine and process for the fabrication of such micro parts and components. Unlike normal size part, micro part can only be manufactured through two techniques namely up-scaling and down-scaling processes [6]. Between these two categories, the down-scaling technique such as micro-machining, micro-turning, micro-electrical discharge machining and micro grinding are preferred based on its robustness, consistency and cost effective [7]. However, the challenges with the down-scaling technique are due to its process stability and materials behavior especially for thin and micro size difficult-to-machine materials [8]. In addition, machining of high-performance material such as titanium can be problematic in terms of slow material removal rate (MRR) and rough machined surface.

One of the most important factors that influences the machining performances for micro size component is the cutting force resulting from the physical contact between tool and workpiece. Owing to this, the allowable machinable diameter size are limited and dependent with the workpiece material's type and properties. As the cross section of micro cylindrical part is decrease, its rigidity will also decrease and cause the deflection of the workpiece from the normal axis. The workpiece deflection will result in dimensional surface errors and affect part accuracy [9-10]. Although micro turning appears as one of the most versatile processes for producing micro-cylindrical or rotational symmetry workpieces, unfortunately, the main barrier with micro turning process is the radial cutting force which deflects the workpiece and significantly affect the part accuracy as depicted in Figure 2.

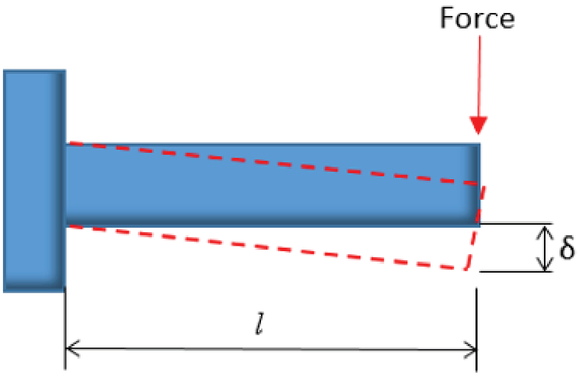

Figure 2: Part deflection toward the cutting force direction

During the operation, the thrust force is carefully considered to control the workpiece deflection which limit the machinable parts size due to the elastic deformation of the micro tool and/or the workpiece. The workpieces prone to vibrate in the tangential direction of the tool - workpiece contact region since the vibration along the tangential direction is constrained by the cutting tool. In addition, the combination of excessive radial cutting force and vibrating machine tool will lead to premature tool failure and broken tool [11]. Other than that, the deflection will affect the part accuracy and slow down the production.

Based on the discrepancies of current manufacturing technique for micro-machining of micro size components, this paper proposes a new non-contact material removal process. Adopted from the wire electrical spark erosion process, a new hybrid micro-machining process is developed by incorporating with rotating mechanism to rotate the workpiece. Through this non-contact material removal process, the cutting force are minimized or in other words, can be neglected.

However, incorporating wire EDM to remove material in symmetrical cylindrical shape component causing several challenges especially with regards to the process stability. One of the most important factors that affect the WEDT machining performances is the rotational spindle speed as it will alter the spark discharge performance as compared with normal WEDM. Therefore, knowledge and understanding on the effects of WEDT rotation speed towards part performances namely surface roughness (Ra) and material removal rate (MRR) are necessitate for the success of machining.

2.0 METHODOLOGY

In this experiment, a dedicated rotary axis mechanism was developed and installed on Mitsubishi Ra-90 table as shown in Figure 3 and Figure 4, respectively. Mitsubishi Ra-90 is non-submersible type of WEDM machine. All machining trials were carried out with constant machining parameter obtained from Mitsubishi Ra-90 machine library and machining characteristics E-Pack E5241 (Table 1). In this work, the spindle speed was varied between 500 to 1500 rpm. A brass electrode wire with diameter of 0.25 mm, 0.7 mm/min table feed, 15 mm workpiece overhang and 1 mm radial depth of cut were employed in the machining tests. Deionized water was used as a working fluid and pumped with a high pressure into the machining gap from upper and lower nozzle. A commercially available Ti6Al4V rod with diameter of 9.49 mm was used for the work material for experimentation.

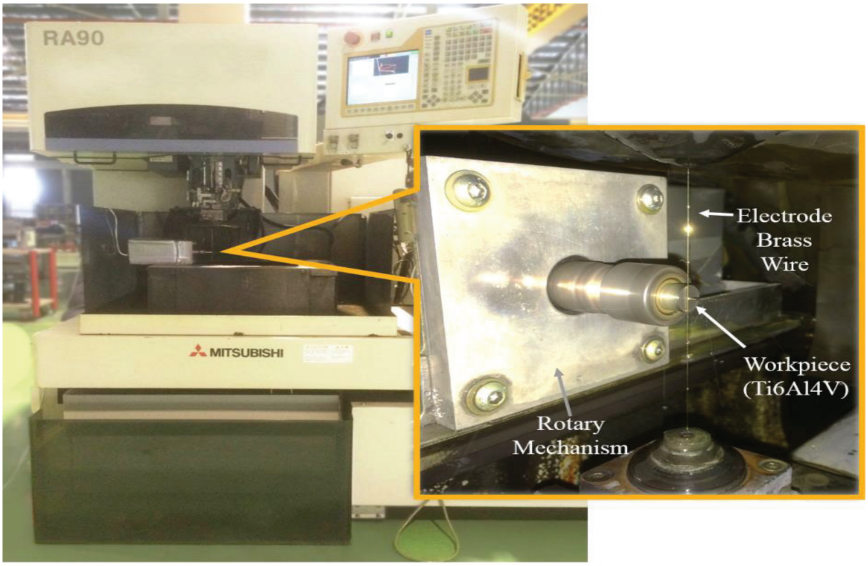

Figure 3: Experimental setup of WEDT rotary axis mechanism installed on Mitsubishi Ra-90 worktable

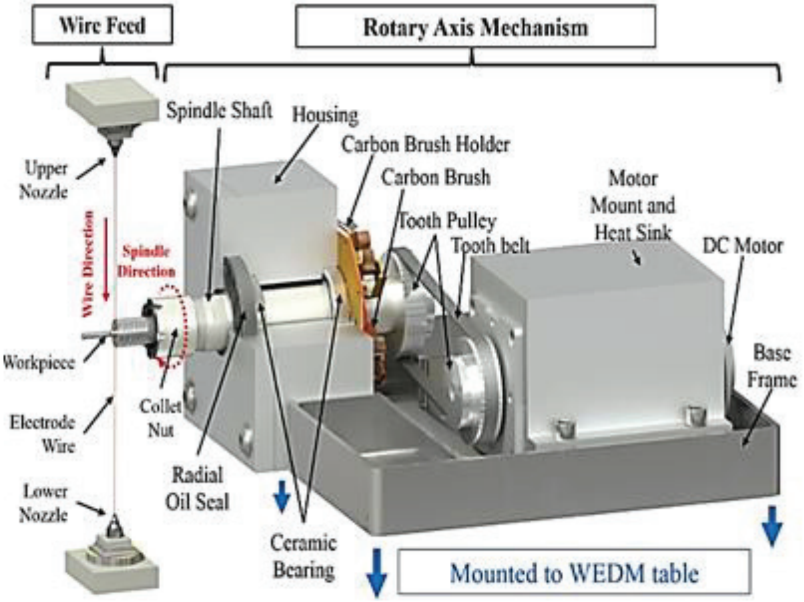

Figure 4: Details of WEDT rotary axis mechanism

Table 1: Mitsubishi Ra-90 parameters and their descriptions (Mitsubishi-Electric-Corporation)

Parameters	Value (Notch)	Descriptions
Voltage open, Vo	16	This switch sets the height of the gap voltage during no-load.
Power Setting, IP	10	This switch sets the size of the peak current that flows the gap.
Off Time, OFF	1	Switch to sets the time between end of discharge and new voltage applied.
Stabilizer A, SA	4	This switch determines the machining stability and is used to finely adjust the current. The higher the value is, the faster the machining speed will be but chance of wire breaks is higher.
Stabilizer B, SB	9	This switch determines the machining stability. The higher the value, the slower the machining speed.
Stabilizer C, SC	1	This switch is used to stabilize machining for the finishing circuit. The higher the value will stable the machining condition but result in poor surface finish.
Stabilizer E, SE	5	This switch sets the machining stability. As the notch value increase, the machining become slower, but prevent the wire from easily break.
Voltage Gap, VG	50 Volts	This switch sets the average machining voltage used as a target value when machining with optimum feed.
Wire Speed, WS	12	This switch sets the wire feed rate. The higher the value, the faster the wire feed rate.
Wire Tension, WT	11	This switch sets the wire tension. The higher the value, the higher the tension of wire.
Pre-Tension, PT	14	This switch sets the wire pretension. The higher the value, the higher the pretension of wire.
Liquid Quantity, LQ	2	This switch sets strong of the dielectric fluid flow rate.
Liquid Resistivity, LR	9	This switch sets the specific resistivity of the dielectric fluid. The higher the value, the lower specific resistivity.

The arithmetic average roughness (Ra) was measured by Mitutoyo Surftest SJ-301 portable surface roughness with 0.8 mm cut off length [12]. The direction of the measurement was made perpendicular to wire feed direction. The diameter for MRR calculation was measured by using Mitutoyo Toolmaker's Microscope and theoretical Equation (1) was used to calculate for MRR.

$$MRR = \pi L(R^2 - r^2)/t \ (mm^3/min) \tag{1}$$

where R denoted the initial part radius (mm); r denoted the final radius after machining (mm); L denoted machining length (mm) and t denoted the machining time (min).

The experiments for every rotational spindle speed were replicated four times for consistency. Descriptive statistics and relevant plots were used to summarize the experiment results. Furthermore, one-way analysis of variance (ANOVA) were used to analyze the significant differences between the group through statistical software package Minitab 16 as appropriate at α= 0.05 level of significance. Subsequently followed by Tukey's multiple comparison to ascertain the differences between rotational spindle speed statistically. In this multiple comparison method, the statistical significance differences were used to assess the differences between means through a set of confidence intervals, hypothesis tests or both. The advantages of employing Tukey's multiple comparison are due to its robustness with respect to unequal group sample sizes and simple calculation.

3.0 RESULTS AND DISCUSSION

3.1 Effects of Rotational Spindle Speed on Material Removal Rate (MRR)

Figure 5 and Figure 6 show the results of the S/N ratio and Box plots of MRR toward rotational spindle speed, respectively. It shows that there is significant changes on MRR value as the rotational spindle speed increases. By increasing rotational spindle speed from 50 rpm to 100 rpm has led to MRR reduces from 17.766 to 17.656 mm^3/min. Further increment in rotational spindle speed from 100 to 400 rpm has increases the MRR to 17.863 mm^3/min which was the highest MRR for the rotational spindle speed ranges. It was observed that, at 700 to 1300 rpm, MRR decreases dramatically to 17.144 mm^3/min and fluctuated for the following rotational spindle speed with decreasing trends. The lowest MRR value was observed at 2200 rpm as much as 16.636 mm^3/min. The obtained fluctuation trends of MRR were found similar as reported by Janardhan and Samuel [13] in which material removal rate will increase by increasing the rotational spindle speed at certain rpm and then decreased. One of the possible reasons are due to the increases number of arcs and arc regions at the cutting zone. In addition, Geng et al. [14] stated that at certain range of rotational spindle speed, the MRR improves due to the rotational motion of workpieces that dissipate the heat on wire electrode surface and subsequently improves the debris removal process. However, if rotational spindle speed exceeds the limit, the discharge become insufficient and value of the MRR decreases as agreed by Janardhan and Samuel [13]. The confidence in Janardhan and Samuel [13] results also can be proved by the wire breakage at 2500 rpm due to energy spent per unit length reduced. Apart from that, too high rotational spindle speed will cause severe vibration that affect the machining process stability.

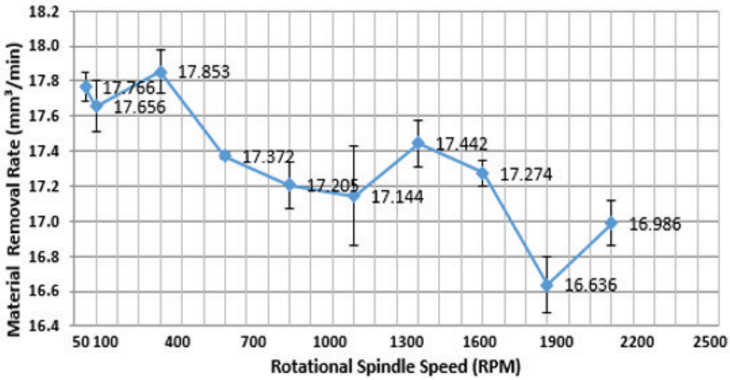

Figure 5: Effect of different rotational spindle speeds on the material removal rates

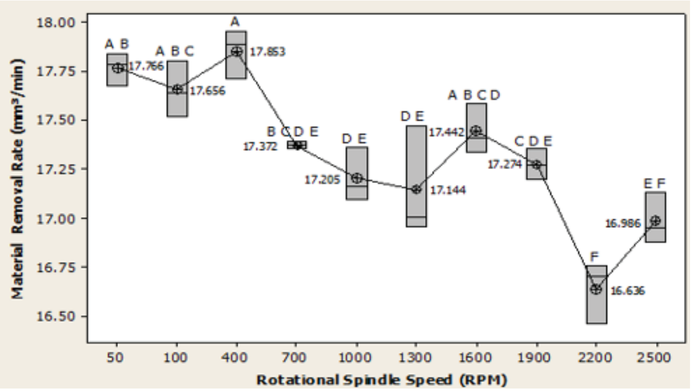

Figure 6: Box plots of the rotational spindle speeds on the material removal rate (MRR)

Mean of MRR among each rotational spindle speed were significantly difference ($p=0.000$, one-way ANOVA). By employing Tukey's family error method to account for multiple comparison, it was found that at 400 rpm rotational spindle speed; the highest MRR was produced with 17.853 mm^3/min that significantly different among 700, 1000, 1300, 1900, 2200 and 2500 rpm. Other than that, no significance different for 50, 100 and 1600 RPM of rotational spindle speed with 400 rpm. While the lowest MRR produced was 16.636 mm^3/min at 2200 rpm. According to Tukey's family error method, 2200 rpm has no significance different except with 2500 rpm (mean= 16.986 mm^3/min) compared to the other rotational spindle speed. However, 2500 rpm shared same letter with 700 rpm to 1300 rpm and 1900 rpm which means it has no significant difference among that rotational spindle speed. 50 rpm (mean= 17.766 mm^3/min) was the lowest rotational spindle speed in this experiment and one of the rotational spindle speeds that produced the highest MRR after 400 rpm. As shown in Figure 6, at 50 rpm no significant difference with 100 rpm, 700 rpm and 1600 rpm as grouped by same letter. At the same time, the difference can only be seen with 1900 rpm to 2500 rpm, 1000 rpm and 1300 rpm rotational spindle speed.

3.2 Effects of Rotational Spindle Speed on Surface Roughness (Ra)

Figures 7 and 8 show the results of the S/N ratio and Box plots of the surface roughness (Ra) toward rotational spindle speed, respectively. Mean of surface roughness (Ra) value among each of rotational spindle speed was significantly different (p=0.000, one-way ANOVA). Tukey's family error method indicated that 2500 rpm significantly produced the lowest surface roughness (Ra) value (mean= 4.468 μm) compared to the other rotational spindle speed values although it has no significant different with other spindle speeds.

Furthermore, small variations were found between 100 rpm to 1300 rpm spindle speeds which indicated there were no significant difference although it was in the same family group (denoted as A and B letter). The highest surface roughness value was obtained at 50 rpm (mean= 7.548 μm) which belong to the same family group with 100, 400, 700, 1000 and 1300 rpm. One thing to be highlighted, 100 rpm spindle speed (low spindle speed) was in the same group with 1600 rpm and 1900 rpm (high spindle speed) and denoted as C letter. One of the possible reasons of this occurrence may be due to the stability of spark produced resulting from combination of 100 rpm and 0.7 mm/min table feed.

The results revealed that, descriptive graph unable to indicate the significance difference between the results as compared to Tukey's multiple comparison method. Surface roughness value begin to reduce when spindle speed at 1300 rpm to 2500 rpm, which from 7.178 μm to 4.468 μm. The result shows that by using high spindle speed in WEDT capable to produce low surface roughness value on machined surface. It indicated that, as the circumferential length of the workpiece material overpass the spark region increased, the energy spent per unit length are diminished as the number of arc regions are increased. Figure 9 shows the machined surface on lateral surface of cylindrical parts micro-turning scanned by scanning electron microscope (SEM) and the pseudo-colour that is scanned by Alicona IFM. It was found that the occurrence of macro-ridges surface as a result from the spark discharge process.

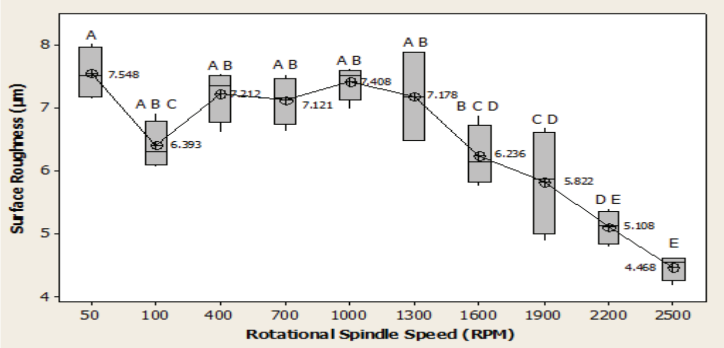

Figure 7: Effect of different rotational spindle speeds on the surface roughness

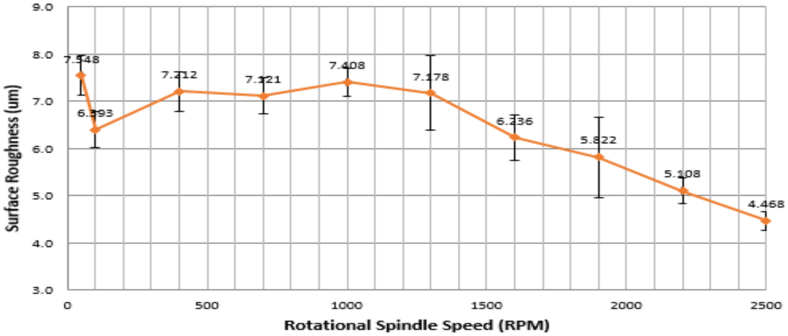

Figure 8: Box plots for different rotational spindle speeds on the surface roughness

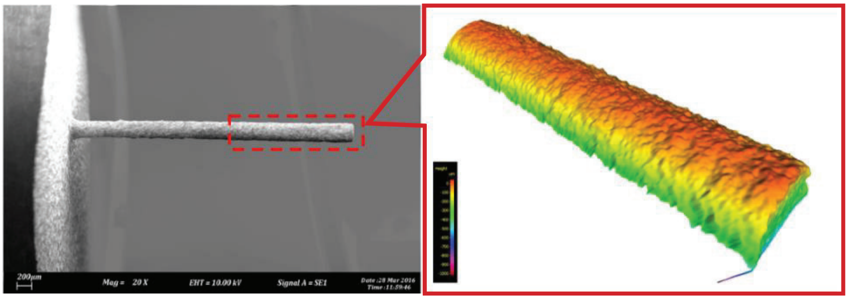

Figure 9: SEM and IFM of micro-turning part by WEDT

4.0 CONCLUSION

This study performs a statistical evaluation on the effects of wire EDM turning (WEDT) rotational speed on material removal rate (MRR) and surface roughness (Ra). The results obtained from the experimental tests were highlighted:

i. Increasing the rotational spindle speed does not improve material removal rate. In contrast, increasing rotational spindle speed susceptible to decrease the MRR trend. At the highest rotational spindle speed which was at 2500 rpm, it was found that wire breakage was frequently occurred due to extreme vibration and dropped in material removal rate.
ii. Statistical analysis like one-way analysis of variance (ANOVA) and Tukey's multiple comparison employed in this study have been produced meaningful disparity among rotational spindle speed, surface roughness (Ra) and material removal rate (MRR). The statistical results revealed there was a significant difference on certain values of rotational spindle speed which provide the relationship between the pairwise configuration.
iii. The results of surface roughness and material removal rate clearly reflected the capability of employing WEDT process using the rotary axis mechanism attached to the WEDM machine. The expedient in the selection of the optimal rotational spindle speed value has the potential to bring the machining parts to the desired quality.

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