PARAMETRIC STUDY ON PARAMETER EFFECTS IN HYBRID MICRO WIRE ELECTRICAL DISCHARGE TURNING

R. Izamshah, M. Akmal, M.S. Kasim, M.K. Sued, S.A. Sundi and M. Amran

Precision Machining Group, Faculty of Manufacturing Engineering,
Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya,
76100 Durian Tunggal, Melaka, Malaysia.

Corresponding Author's Email: izamshah@utem.edu.my

Article History: Received 28 April 2017; Revised 23 August 2017; Accepted 7 February 2018

ABSTRACT: In this work, a comprehensive parametric study on the effects of operating parameters in wire electrical discharge turning (WEDT) process was conducted. A total of eleven operating parameters were considered against the machined surface quality. The research focuses on the micro-turning of Ti6Al4V materials using Taguchi's L12 orthogonal array at two-level experimental designs. Analysis of variance (ANOVA) and signal-to-noise (S/N) ratio were used as statistical tools to evaluate the significance of the parameters. It was found that among the eleven operating parameters, only four parameters dominated and had statistical significant effects on the surface roughness values as discovered by ANOVA. The operating parameters were the rotational spindle speed (28.34%) as the most dominating factor, followed by intensity of pulse (24.18%), wire tension (20.57%) and stabilizer E (11.97%).

KEYWORDS: *WEDT; Operating Parameters; Taguchi; Ti6Al4V; Surface Roughness*

1.0 INTRODUCTION

Wire electrical discharge turning (WEDT) is a non-conventional machining process which evolved from the basis of wire electrical discharge machining (WEDM) a few decades ago. It was introduced by Qu [1] to countermeasure the issues in turning raw form of difficult-to-machine materials into profile form shapes. Turning of the low machinability materials such as titanium and its alloy by conventional process created difficulties, and for that reason development in this area has seen steady growth [2- 3]. A free cutting force process such as electrical discharge based machining combining with the rotating workpiece could be a suitable candidate [4]. Presently, WEDT has been given considerable attention owing to the rapid innovation in modern industrial micro part. WEDT is proven efficient in performing the turning process at the micro dimension level with high accuracy [5-6], improving material removal rate [6-8] and increasing cutting capabilities [7]. Despite the aforementioned effectiveness, there has been an increasing concern on the quality of the surface finish obtained by micro WEDT process regarding the alteration of the operating parameters. Due to the huge number of parameters involved in WEDT, not many works have been done on evaluation of each of the operating parameters against the surface roughness for micro parts turning. Taguchi technique is a significant approach to help in simplifying the experimental investigation to lessen the time as well as being effective in multiple factors investigations in the field of manufacturing [9]. Taguchi approach recommends an orthogonal array (OA) designed by varying each factor level in a systematic manner that combines an inner array of control factors with an outer array of noise factors. Taguchi approach also provides more complete information than typical fractional factorial designs [10–12] which contributes to a better understanding among the operating parameters. In the present study, an attempt has been made to investigate all the operating parameters in WEDT for performing micro-turning of parts considering arithmetic average surface roughness (Ra) as performance criteria. This research intends to establish the main effects of the WEDT operating parameters by Taguchi approach as design and analysis method.

2.0 EXPERIMENT DETAILS

2.1 Test setup, Material and Measurement

A WEDT rotary axis mechanism unit was placed on the table of commercial WEDM machine (Mitsubishi RA90) as shown in Figure 1 (a). A Ti6Al4V rod with a diameter of about 9.49 mm was used as the workpiece material and machined by brass electrode wire with a diameter of 0.25 mm. Ti6Al4V material is known as difficult-to-machine material by conventional processes [13–14] but is widely used in modern application because of its light weight and biocompatibility properties. Table 1 depicts the Ti6Al4V material properties. In this experiment, single pass cutting was employed throughout the experiment for fabricated 4 mm in length straight micro-shaft. Surface roughness of the machined parts is assigned as the response and measured by non-contact type Alicona infinite focus microscope (IFM) as shown in Figure 1 (b).

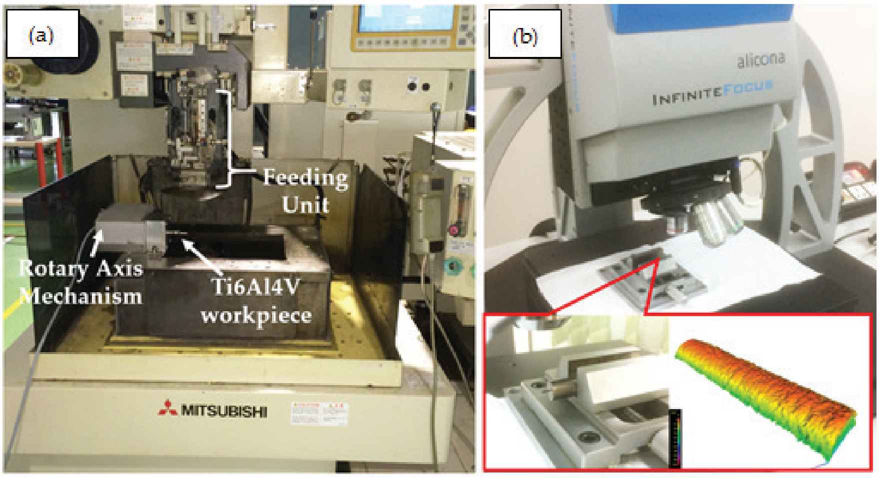

Figure 1: (a) A rotary axis mechanism installed on Mitsubishi RA90 worktable and (b) Alicona infinite focus microscope (IFM)

Table 1: Ti6Al4V material properties

Density (g/cm^3)	Hardness Rockwell C	Elastic Modulus (GPa)	Tensile Strength (MPa)
4.42	36	114	1000

2.2 Design of experiments using Taguchi method

There are two different analysis approaches in Taguchi; first by using the average of repetitive runs that are treated by main effect and analysis of variance (ANOVA). Second, by performing multiple runs and treating it by using S/N ratio [15]. Taguchi L_{12} orthogonal array (2^{11}) was used as the experimental design to establish the optimum operating parameters by means of S/N ratio analysis and to estimate the contribution of individual parameter using ANOVA. Table 2 shows the orthogonal array for L_{12} of Taguchi method employed in the present study. There are 11 operating parameters selected which are voltage open, intensity of pulse, stabilizer A, stabilizer B, stabilizer E, voltage gap, wire speed, wire tension, rotational spindle speed, feed rate and spindle direction. Table 3 shows the parameters and their descriptions. Each parameter is divided into two levels (1 and 2) as indicated in Table 4.

Table 2: L_{12} orthogonal array for eleven factors and two levels (211) [15]

Experiment Number	Column/Factor										
1	A	B	C	D	E	F	G	H	I	J	K
2	1	1	1	1	1	1	1	1	1	1	1
3	1	1	1	1	1	2	2	2	2	2	2
4	1	1	2	2	2	1	1	1	2	2	2
5	1	2	1	2	2	1	2	2	1	1	2
6	1	2	2	1	2	2	1	2	1	2	1
7	1	2	2	2	1	2	2	1	2	1	1
8	2	1	2	2	1	1	2	2	1	2	1
9	2	1	2	1	2	2	2	1	1	1	2
10	2	1	1	2	2	2	1	2	2	1	1
11	2	2	2	1	1	1	1	2	2	1	2
12	2	2	1	2	1	2	1	1	1	2	2
	2	2	1	1	2	1	2	1	2	2	1
A, B, C, D, E, F, G, H, I, J and K = Factor 1 and 2 = Level											

Table 3: Mitsubishi RA90 parameters and their descriptions [16]

Parameters	Descriptions
Voltage Open	This switch sets the height of the gap voltage during no-load. Voltage increases for larger value
Intensity of Pulse	This switch sets the size of the peak current that flows the gap
Stabilizer A	This switch determines the machining stability and is used to finely adjust the current. The higher the value is, the faster the machining speed
Stabilizer B	This switch determines the machining stability. The higher the value, the slower the machining speed
Stabilizer E	This switch sets the machining stability. As the value increases, the machining becomes slower but wire is difficult to break
Voltage Gap	This switch sets the average machining voltage used as a target value when machining with optimum feed
Wire Speed	This switch sets the wire feed rate. The higher the value, the faster the wire feed rate
Wire Tension	This switch sets the wire tension. The higher the value, the higher the tension of wire
Rotational Spindle Speed	Angular velocity of the spindle expressed in revolutions per minute

Table Feed rate	The velocity cutting speed of the table during machining which is controlled by the servo mechanism
Spindle Direction	Direction of the spindle rotation. Downward direction follows the direction of the wire travelling direction and Upward is opposite to the wire travelling direction

In the present study, the lower value of arithmetic average (Ra) is prioritized. Therefore, "the-small-better" formula is applied to calculate the S/N ratio of Ra. The higher value of the S/N ratio is required to achieve stable quality. 12 experiments were conducted using Taguchi experimental design method and there were two replicates for each experiment to obtain S/N values.

Table 4: Eleven design variable, unit and levels for Taguchi L12

Parameter	**Unit**	**Level**	
		1	**2**
Voltage Open	Notch	6	8
Intensity of Pulse	Notch	8	10
Stabilizer A	Notch	1	3
Stabilizer B	Notch	6	12
Stabilizer E	Notch	2	5
Voltage Gap	volt	40	140
Wire Speed	Notch	10	16
Wire Tension	Newton	10.6	14.8
Rotational Spindle Speed	rev/min	50	2400
Table Feed rate	mm/min	0.05	0.1
Spindle Direction	-	Upward	Downward

3.0 RESULTS AND DISCUSSION

Table 5 and Table 6 show the results and the analysis of the S/N ratio for arithmetic average surface roughness (Ra). Figure 2 illustrates the grayscale image of micro-turning of straight shaft scanned by scanning electron microscope (SEM) and the pseudo-colour that is scanned by Alicona IFM to obtain the arithmetic average surface roughness. Among all the parameters, rotational spindle speed has a large contribution to the Ra result as much as 28.34% followed by pulse intensity and wire tension as much as 24.18% and 20.57% respectively (Table 6). Compared to the other parameters, these three parameters contribute to ~20% which indicates extraordinary influences from the Ra value. The three parameters also are in the top three ranking among 11 parameters. Apart from that, the results of the Ra also has a quite high contribution by stabilizer E with 11.97% of contribution followed by voltage open, stabilizer B and spindle direction with percentage contribution as much as 7.44%, 3.05% and 2.9% respectively. The other parameters indicated less influence on the Ra as percentage contribution is less than 1%. The parameters are wire speed, voltage gap, table feed rate and stabilizer A with percentage contribution as much as 0.65%, 0.51%, 0.34% and 0.064% respectively.

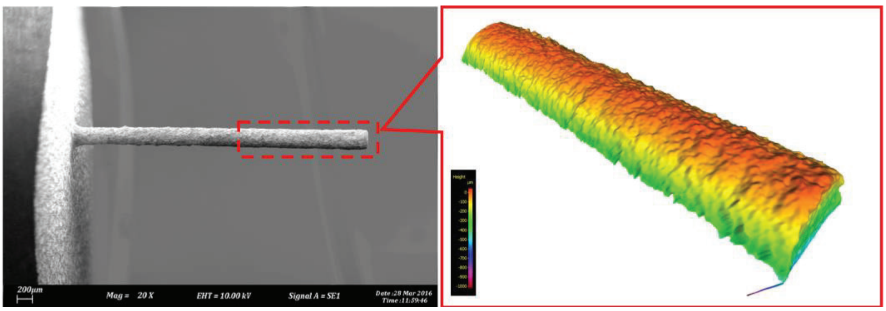

Figure 2: SEM and IFM of micro-turning part by WEDT

Table 5: Experimental results

	Arithmetic average surface roughness (µm)		
Trial No.	**Ra1**	**Ra2**	**S/N Ratio**
1	6.578	6.39	-16.2341
2	3.890	4.16	-12.0974
3	6.023	6.09	-15.6424
4	4.848	5.17	-14.0013
5	5.930	5.30	-14.9988
6	4.525	4.54	-13.122
7	5.063	5.14	-14.1516
8	4.523	5.19	-13.7465
9	5.220	5.72	-14.7688
10	6.525	6.35	-16.1718
11	6.868	6.43	-16.4595
12	5.555	5.48	-14.8331

Table 6: Percentage contribution of S/N ratio for Ra

Parameter	Standardized Effects	Sum of Squares	% Contribution	Rank
Voltage Open	0.7	1.46	7.44	5
Intensity of Pulse	-1.26	4.73	24.18	2
Stabilizer A	0.064	0.012	0.064	11
Stabilizer B	0.45	0.6	3.05	6
Stabilizer E	0.88	2.34	11.97	4
Voltage Gap	-0.18	0.1	0.51	9
Wire Speed	-0.21	0.13	0.65	8
Wire Tension	1.16	4.03	20.57	3
Spindle Speed	1.36	5.55	28.34	1
Feed rate	0.15	0.066	0.34	10
Spindle Direction	0.43	0.57	2.9	7

For the purpose of obtaining the P-value, the stabilizer A as parameter is excluded to allow the analysis by ANOVA in Minitab Software. Stabilizer A was left out during ANOVA because the contribution of that factor was inadequate. Table 7 shows the results for ANOVA to further analyse the statistical effects of operating parameters on Ra. ANOVA was used to identify the significance among the parameters on the Ra in statistical point of view. The ANOVA results indicated, the most significant factor according to the lowest P-value were rotational spindle speed, intensity of pulse, wire tension and stabilizer E. Other than that, only voltage open approached an acceptable significance level with P-value 0.059. The other parameters possess none statistical effects on Ra with massive P-value is greater than 0.05.

Table 7: S/N ratio ANOVA for Ra

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	10	19.5622	1.95622	156.86	0.062
Voltage Open	1	1.4555	1.45549	116.71	0.059
Intensity of Pulse	1	4.7323	4.73233	379.45	0.033
Stabilizer B	1	0.5967	0.59667	47.84	0.091
Stabilizer E	1	2.3429	2.34294	187.86	0.046
Voltage Gap	1	0.0999	0.09987	8.01	0.216
Wire Speed	1	0.1278	0.12783	10.25	0.193
Wire Tension	1	4.0266	4.02664	322.87	0.035
Rotational Spindle Speed	1	5.5469	5.54687	444.76	0.030
Table Feed rate	1	0.0664	0.06639	5.32	0.260

Spindle Direction	1	0.5672	0.56722	45.48	0.094
Error	1	0.0125	0.01247		
Total	11	19.5747			

Figure 3 shows the main effects of the S/N ratio for each of the operating parameters that were conducted by WEDT for turning micro-cylindrical parts. Among the factors studied, rotational spindle speed, pulse intensity and wire tension dominated the Ra value as listed in Table 6. The S/N ratio plots for these three factors have shown dramatic trend line by changing the level of the parameter. For pulse intensity, by increasing the parameter level 8 to 10 Notch, the Ra increased. The low Ra was able to be achieved at 8 Notch. This could be explained in terms of energy produced in the erosion process. By increasing the pulse intensity, it led to the increase of the energy which generated large size of crater [17].

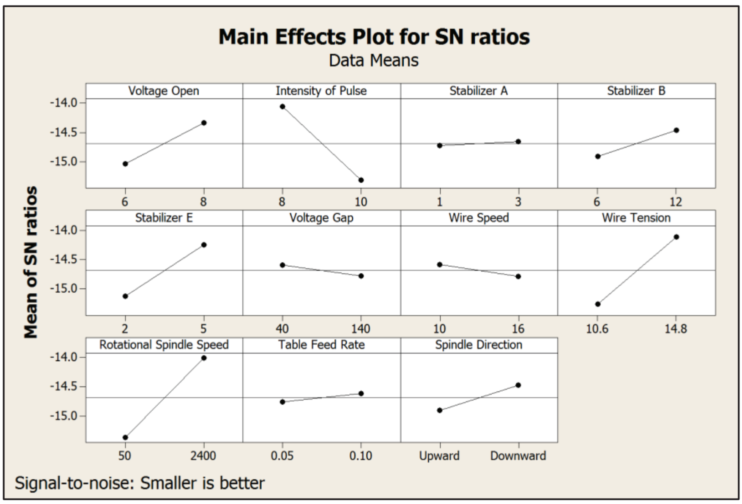

Figure 3: Main effects plot for S/N ratios of Ra results

For rotational spindle speed and wire tension, the lowest Ra was generated at a high parameter level. From the S/N ratio of rotational spindle speed plotted, the lowest Ra was achieved by using 2400 rev/min. By increasing the spindle speed from 50 rev/min to 2400 rev/min, the Ra dramatically decreased. These results are consistent with other studies which indicated the lowest surface roughness value is produced by increasing rotational spindle speed [18]. This is because, when the circumferential length of the workpiece material overpass the spark region is increased, the energy spent per unit length is diminished because the number of arc regions is increased [19]. Furthermore, from the S/N ratio of wire tension plotted, the graph indicates that the lowest Ra was obtained by using an electrode wire with 14.8 N tensions. This result corresponds with the previous research done in which the higher the tension of electrode wire reduced the wire deflection that can lead to fine surface roughness [20]. According to Mitsubishi RA90 parameter library, stabilizer E is specified as the switch for controlling the machining stability. As the notch value increases, the machining becomes slower but the wire is difficult to break. By referring to the pulse waveforms that are provided by Mitsubishi RA90, the stabilizer E fundamentally is denoted as short/arc circuit current controller as indicated in Figure 4. Stabilizer E is proven to have statistical significant effects on Ra value. Therefore, this phenomenon is related to the abnormality on WEDM process but it is normal in WEDT.

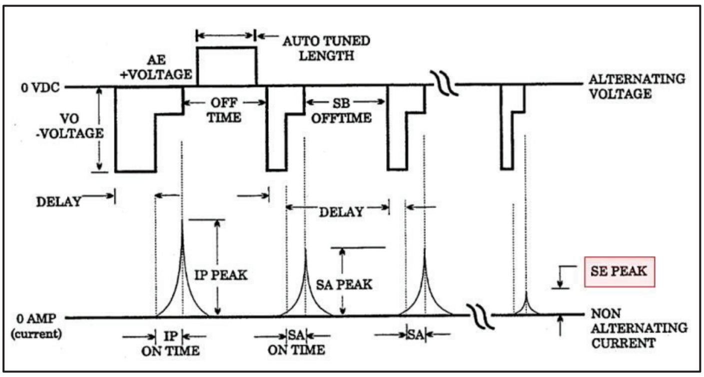

Figure 4: Mitsubishi RA90 theoretical pulse waveforms

In WEDT, the presence of the rotary axis mechanism in WEDM inadvertently changes the characteristic of the pulses. Compared to the WEDM, the waveforms for WEDT contain a lot of arc regions which means the energy to produce the plasma is not sufficient. Additionally, the S/N ratio plot also shows the effects of open voltage on surface roughness. By increasing the open voltage from 6 to 8 Notch the Ra value is reduced. Contrary to expectations, this voltage results did not find similar trends like pulse intensity. However, these results are in agreement with those obtained by Mohammadi [20] which indicated that voltage does not have statistical significant effects on the Ra with P-value = 0.059 (Table 7). According to Mitsubishi RA90 parameter library, stabilizer B is specified as the switch to obtain machining stability. This stabilizer B is related to the off time in pulse waveforms. The higher the value, the higher the off time of the machining process. It frequently occurs which also generate slower machining process. The Ra value is decreased by increasing the level of parameter from 6 to 12 Notch which means the number of sparks falls off. Only spindle direction is categorized as categorical factor. As shown in surface roughness S/N ratio plotted, the downward direction produced the lowest Ra value. This is probably related to the arcing which occurred more frequently due to the spark gap becoming smaller when the spindle is rotated in opposite direction to the electrode wire travelling (upward direction) which leads to the deterioration of the machined surface. As indicated by Table 7, the less influencing parameters on the Ra in this study which possess less than 1% of contribution percentage were wire speed, voltage gap, table feed rate and stabilizer A. In spite of possessing little effects on the Ra, the results of the S/N ratio plot are useful to optimize this study. All photographs and figures should have a good resolution and contrast quality. At least 300 dpi is applied for the resolution.

4.0 CONCLUSION

L12 Taguchi design method in this study is able to establish the main effects of WEDT operating parameters and relationship towards the surface roughness. The obtained results are summarized as follows.

1. The significant factors of the WEDT operating parameters were determined by ANOVA. The rotational spindle speed was the most dominating factor, followed by intensity of pulse, wire tension and stabilizer E on the machined surface finish value.
2. The surface roughness decreased when rotational spindle speed, stabilizer E and wire tension were applied at high level. At the same time, the intensity of pulse was applied at low level.
3. High pulse intensity produced large energy of plasma channel that generated large size of craters which led to poor surface finish.
4. Excellent surface finish was obtained by less deflection of electrode wire when high tension was applied during machining, meanwhile less energy was produced when high speed of spindle rotation and high level of stabilizer E were applied. By increasing the spindle rotation speed therefore the number of arc regions also increased which useful for reducing the spark energy.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the Faculty of Manufacturing Engineering, Universiti Teknikal Malaysia Melaka (UTeM) for experimental facilities used in this project and Malaysian Ministry of Higher Education for Fundamental Research Grant Scheme (FRGS); FRGS/2/2014/TK01/UTEM/03/2.

REFERENCES

[1] J. Qu, A. J. Shih, and R. O. Scattergood, "Development of the cylindrical wire electrical discharge machining process, part 2: Surface integrity and roundness," *Journal of Manufacturing Science and Engineering, Transactions of the ASME*, vol. 124, no. 3, pp. 708–714, 2002.

[2] A. Pramanik, "Problems and solutions in machining titanium alloys," *International Journal of Advanced Manufacturing Technology,* vol. 70, pp. 919-928, 2014.

[3] V. Bhemuni, "Investigations of Forces, Power and Surface Roughness in Hard Turning with Mixed Ceramic Tool," *Journal of Advanced Manufacturing Technology,* vol. 10, no. 1, pp. 107–120, 2016.

[4] R. Izamshah, M. Akmal, M. S. Kasim, S. A. Sundi, and M. Hadzley, "A statistical comparison in selection of wire-EDM process parameters for machining titanium alloy," *Journal of Advanced Manufacturing Technology,* vol. 10, no. 2, pp. 45-55, 2016.

[5] Y. Zhu, T. Liang, L. Gu, and W. Zhao, "Machining of Micro Rotational Parts with Wire EDM Machine," *Procedia Manufacturing,* vol. 5, pp. 849–856, 2016.

[6] M. Akmal, R. Izamshah, M. S. Kasim, M. Hadzley, M. Amran, and A. Ramli, "Development of a rotary axis mechanism for wire EDM turning (WEDT)," in Mechanical Engineering Research Day 2016, Melaka, Malaysia, 2016, pp. 62–63.

[7] X. Geng, G. Chi, Y. Wang, and Z. Wang, "Study on Microrotating Structure Using Microwire Electrical Discharge Machining," *Materials and Manufacturing Processes,* vol. 29, no. 3, pp. 274–280, 2014.

[8] A. Mohammadi, A. F. Tehrani, and A. Abdullah, "Introducing a New Technique in Wire Electrical Discharge Turning and Evaluating Ultrasonic Vibration on Material Removal Rate," *Procedia CIRP,* vol. 205, no. 1, pp. 283–289, 2008.

[9] F. Nourbakhsh, K. P. Rajurkar, A. P. Malshe, and J. Cao, "Wire Electro-Discharge Machining of Titanium Alloy," *Procedia CIRP,* vol. 6, pp. 583-588, 2013.

[10] M. A. Ali, M. Samsul, N. I. S. Hussein, M. Rizal, R. Izamshah, M. Hadzley, M. S. Kasim, M. A. Sulaiman and S. Sivarao, "The effect of EDM die-sinking parameters on material removal rate of beryllium copper using full factorial method," *Middle-East Journal of Scientific Research,* vol. 16, no. 1, pp. 44-50, 2013.

[11] S. G. Choi, S. H. Kim, W. K. Choi, and E. S. Lee, "The optimum condition selection of electrochemical polishing and surface analysis of the stainless steel 316L by the Taguchi method," *International Journal of Advanced Manufacturing Technology,* vol. 82, no. 9-12, pp. 1933–1939, 2016.

[12] R. Zuraimi, M. A. Sulaiman, T. J. Sahaya Anand, E. Mohamad, and C. H. C. Haron, "Tool life performance of coated carbide tool on titanium alloy extra low interstitials," *Jurnal Teknologi,* vol. 77, no. 1, pp. 85–93, 2015.

[13] R. I. Raja Abdullah, B. I. Redzuwan, M. S. Abdul Aziz, and M. S. Kasim, "Comparative study of tool wear in milling titanium alloy (Ti-6Al-4V) using PVD and CVD coated cutting tool," *Industrial Lubrication and Tribology,* vol. 69, no. 3, pp. 363-370, 2017.

[14] G. Taguchi, S. Chowdhury, and Y. Wu, *Taguchi's Quality Engineering Handbook.* New Jersey: John Wiley & Sons, 2005.

[15] Mitsubishi-Electric-Corporation. (2012). *RA-90 Manual and Machining Characteristic* [Online]. Available: http://dl.mitsubishielectric.com/dl/fa/document/catalog/edm/k-kl2-0-c0069/K-KL2-0-C0069-B.pdf

[16] A. Giridharan and G. L. Samuel, "Modeling and analysis of crater formation during wire electrical discharge turning (WEDT) process," *The International Journal of Advanced Manufacturing Technology,* vol. 77, no. 5-8, pp. 1229–1247, 2015.

[17] M. Haddad, F. Alihoseini, M. Hadi, M. Hadad, A. Tehrani, and A. Mohammadi, "An experimental investigation of cylindrical wire electrical discharge turning process," *The International Journal of Advanced Manufacturing Technology,* vol. 46, no. 9-12, pp. 1119–1132, 2010.

[18] V. Janardhan and G. L. Samuel, "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,* vol. 50, no. 9, pp. 775–788, 2010.

[19] A. Shah, N. A. Mufti, D. Rakwal, and E. Bamberg, "Material removal rate, kerf, and surface roughness of tungsten carbide machined with wire electrical discharge machining," *Journal of Materials Engineering and Performance,* vol. 20, no. 1, pp. 71–76, 2011.

[20] A. Mohammadi, A. F. Tehrani, E. Emanian, and D. Karimi, "Statistical analysis of wire electrical discharge turning on material removal rate," *Journal of Materials Processing Technology,* vol. 205, no. 1, pp. 283–289, 2008.