Investigation of Areal Surface Roughness during Wire Electric Discharge Turning (WEDT) of Inconel 825

Jees George[1], **Arun V.**[2], **Manu R.**[3], **Jose Mathew**[4]

[1, 2, 3, 4] Department of Mechanical Engineering,
National Institute of Technology Calicut, Calicut 673601, India

Abstract

Wire electrical discharge turning (WEDT) is a non-conventional turning process, which generates precise difficult to machine cylindrical components. An additional rotary axis is fabricated and added to the WEDM machine. Cylindrical Inconel 825 is used as workpiece material. Box Behenken (L27) experimental design is used to perform the experiments. Different process parameters viz. Pulse on time, Pulse off time, Spark Gap and rotational speed were considered while performing the experiments. Areal surface roughness (Sa) value of the turned specimens is measured. The 3D parameter of surface roughness is found to be more appropriate for evaluating the surface quality and it reflects better nature of the topography. Analysis of Variance (ANOVA) is carried out to study the effects different parameters. Based on the analysis it is found that pulse on time and pulse off time are significant factors which affect the areal surface roughness during WEDT process. Optimal levels of process parameters were identified using desirability analysis and validation experiments were performed to confirm the optimized results.

Keywords: WEDM, WEDT, Inconel 825, Areal surface roughness, ANOVA, desirability analysis.

1. INTRODUCTION

Wire Electric discharge machining (WEDM) is a non-conventional machining, which is a thermoelectric process where the material is removed by a series of discrete sparks between workpiece and the wire electrode flushed by a dielectric fluid. The diameter of wire electrode ranges from 0.05 to 0.25 mm. Wire Electric discharge turning (WEDT) is a unique adaptation of WEDM process, which is used to generate precise cylindrical components on hard, difficult to machine materials. The generation of a cylindrical form is obtained by adding a rotary axis to existing WEDM machine. Micro-pins and micro-spindles, which are used to manufacture miniature products with high dimensional accuracy using WEDT process. WEDT process is particularly suitable for turning hard, difficult to machine materials as it is independent of hardness and strength of the material. Inconel 825 is a nickel based aerospace alloy, which is difficult to machine using traditional turning processes. It has higher strain hardening tendency, high dynamic shear strength, and poor thermal diffusivity, which causes difficulty in machining this alloy.

Many researchers have contributed to machining of cylindrical components using WEDT. Giridharan and Samuel proposed a model and analyzed the formation of crater during WEDT process. The author also assessed the effect of input parameters on energy consumption during wire electrical discharge turning process [1]. Haddad et al investigated the effect of machining parameters on surface roughness (Ra) and roundness (RONt) in cylindrical CWEDT of AISI D3 tool steel. Micro ridges and craters on the surfaces of CWEDT parts were examined [2]. Animollah et al achieved a complete realization of the processes parameters and their effects on surface roughness and roundness using Taguchi method [3]. Efforts have been made by many researcher to the development of wire electrical discharge turning setup to carry out turning process. Janardhan and Samuel developed a simple and cost effective WEDT spindle to give rotary motion to the workpiece during WEDT process. The authors observed the influence due to the occurrence of arc regions, width of arc and normal discharge regions and average ignition delay time on surface roughness and roundness error of the WEDT components [4]. Qu et al. designed a precise, flexible, and corrosion- resistant underwater rotary spindle for a conventional two-axis wire EDM machine to enable the generation of free-form cylindrical geometries. The authors also investigated the surface integrity and roundness of parts created by the cylindrical wire EDM process [5,6]. Zhu et al added a precise rotary spindle to a conventional three axis CNC wire EDM machine and performed experiments to fabricate rotational components of small radius and high aspect ratio. The authors conducted a single factor experiment to investigate the influence of radial infeed on MRR. Haddad and Tehrani designed a precise, flexible and corrosion resistance submerged rotary spindle and added to a conventional five axis CNC WEDM machine to enable the generation of free-form cylindrical geometries. They developed a statistical model for MRR to analyze the effects of different process parameters [7]. Krishnan and Samuel developed a model using an artificial neural network with feed-forward back-propagation algorithm and using adaptive neuro-fuzzy inference system for WEDT process [8]. Naresh et al. conducted experiments on Ti-6Al-4V super alloy and analyzed individual and interaction effects on material removal rate (MRR) and surface roughness (Ra) by adopting analysis of variance (ANOVA) in WEDT process. They have also attempted optimization of process parameters using gray relational analysis to derive the optimal WEDT conditions [9]. Nikola et al. developed a mathematical model by neural network programming to study influence of different input parameters on MRR in WEDT process [10]. Animollah et al. employed regression analysis as well as ANOVA on experimental data and studied the effects of different process parameters on MRR [11]. Mohammadi et al. installed an auxiliary device between the two wire-guides, which produce ultrasonic vibrations. The authors show that the wire vibration induced by ultrasonic action has a significant effect on MRR in WEDT process [12]. Loreana et al investigated and compared the results for roughness parameters obtained with the help of two methods of evaluating the quality of the finished surfaces: 2D profilometry and 3D profilometry. The authors found that 3D parameters of surface roughness reflected better nature of the topography [13].

WEDT is a complex and stochastic process and the cylindrical surface produced by this process is a very important factor. The study of surface roughness on the machined components is important as far as the quality of the machining is concerned. Inconel 825 is chosen as the workpiece material. Due to its extreme tough characteristics like high strain rate, high strength, and higher hardness, it is difficult to machine Inconel 825 using conventional machining. WED turned Inconel 825 can have various applications in the manufacturing of micro shafts for radial motors, aerospace industries, electronic sensor pins, in medical industries (neurosurgical implants, maxillofacial micro screws), etc. Most of the researchers have attempted the study of Ra value of surface roughness on WEDT components. Areal surface roughness (Sa) reflects better nature of the topography and is found to be more appropriate for evaluating the surface quality. In the present work, an attempt has been made to study the areal surface roughness (Sa) of machined cylindrical Inconel 825 alloy using WEDT process. Genetic Algorithm (GA) has been used to obtain the optimal combination of process parameters

2. EXPERIMENTAL DETAILS

2.1 Experimental setup

Inconel 825 aerospace alloy is selected as workpiece material to carry out the experiments. The typical chemical composition of Inconel 825 is 38% Nickel, 22% iron, 23.5% Chromium, 3% Molybdenum, 2.5% Copper and 1.2% Titanium. Inconel 825 in cylindrical forms with a dia of 10mm was chosen. Machining length was 10mm for each specimen. Zinc coated brass wire was selected as tool material. The experiments were conducted on ecocut CNC Wire EDM machine where a rotational unit is fabricated and added to the machine in order to produce cylindrical forms. The experiments were aimed at considering the effects of several controllable factors on areal surface roughness. (Sa). The Sa value of surface roughness is measured using Alicona 3d profilometer for each section with a cut off wavelength of 500µm. Fig 1 and 2 shows the turned specimen and the experimental setup.

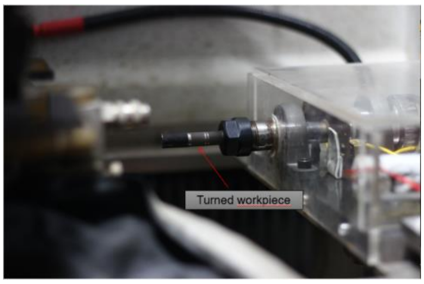

Fig 1. WEDT turned specimen

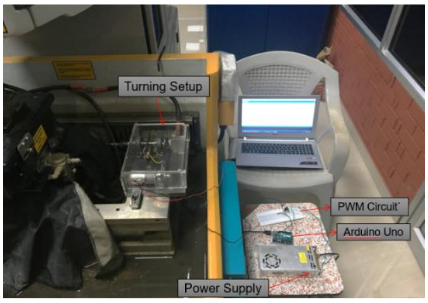

Fig 2. Experimental set up

2.2 Design of Experiments

Factors and their levels are selected as shown in Table 1. Pulse on time, pulse off time, Spark gap and rotational speed are chosen as input parameters to perform the experiments. For each factors three levels are selected. Non-variable parameters in this experiments are shown in Table 2.

Table 1. Factors and their levels

Factor	Levels		
	-1	0	1
Pulse ON time (µs)	10	15	20
Pulse OFF time (µs)	25	30	35
Spark gap (µm)	40	50	60
Rotational speed (rpm)	30	60	90

Table 2. Constant parameters in this experiment

Work material	Inconel 825
Wire speed (m/min)	5
Depth of cut (mm)	0.1
Workpiece diameter (mm)	10.0
Machining length (mm)	10.0

In this research, Box Behenken design of experiment with 27 experimental runs were chosen. Table 3 shows L27 Box Behenken design along with the acquired data for Areal surface roughness

3. DATA ANALYSIS AND DISCUSSION

The factor effects on areal surface roughness is depicted in Fig 3. Fig 3 serves the purpose of graphical assessment. This plot indicates that pulse on time, pulse off time, spark gap and rotational speed have the most significant effect on MRR. It is seen from fig 3 that increasing pulse on time deteriorates the surface of the turned parts. Increasing pulse off time shows a curvature effect on Sa. Areal surface roughness increases with increase in spark which is mainly due to the fact that the area of sparking region reduces with increase in spark gap. Rotational speed doesn’t show any significant effect on Sa.

Table 3. L27 Box Behenken design with the acquired experimental data

Run Order	Pulse ON (µs)	Pulse OFF (µs)	Spark Gap (µm)	Rotational speed (rpm)	Areal surface roughness (µm)
1	10	25	50	60	2.319
2	20	25	50	60	2.932
3	10	35	50	60	2.04
4	20	35	50	60	4.286
5	15	30	40	30	3.862
6	15	30	60	30	3.544
7	15	30	40	90	3.459
8	15	30	60	90	3.521
9	10	30	50	30	3.077
10	20	30	50	30	3.271
11	10	30	50	90	2.358
12	20	30	50	90	4.419
13	15	25	40	60	3.313
14	15	35	40	60	2.433
15	15	25	60	60	2.88
16	15	35	60	60	4.208
17	10	30	40	60	2.492
18	20	30	40	60	3.917
19	10	30	60	60	2.889
20	20	30	60	60	4.56
21	15	25	50	30	2.506
22	15	35	50	30	3.354
23	15	25	50	90	3.393
24	15	35	50	90	3.529
25	15	30	50	60	3.521
26	15	30	50	60	3.614
27	15	30	50	60	3.49

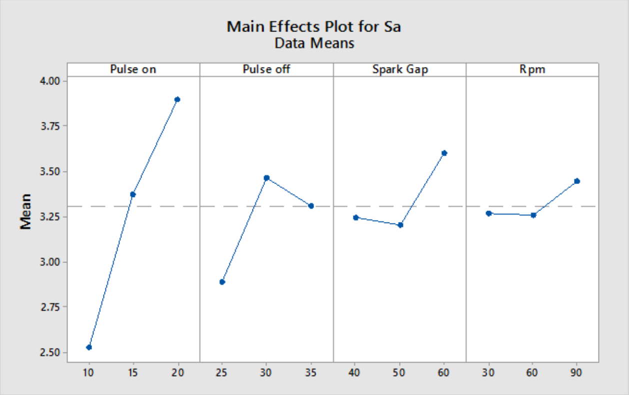

Fig 2. Mean effects plot for Sa

Equation 1 presents the regression equation, which gives the relationship between machining parameters and areal surface roughness.

ANOVA is employed as it covers the shortcomings of graphical assessment. Table 4 presents the modified ANOVA table for areal surface roughness (Sa) using back elimination method. From ANOVA table it is evident that except for rotational speed, all the factors presents a p-value lower than α–level of confidence and thus has significant impact on areal surface roughness.

$$\begin{aligned}&Areal\ surface\ roughness\ (Sa) = \\&8.76 - 0.246\ Pulse\ on + 0.243\ Pulse\ off - 0.3135\ Spark\ Gap - \\&0.0437\ Rpm - 0.00980\ Pulse\ on * \\&Pulse\ on - 0.01663\ Pulse\ off * \\&Pulse\ off + 0.01633\ Pulse\ on * \\&Pulse\ off + 0.003112\ Pulse\ on * \\&Rpm + 0.01104\ Pulse\ off * Spark\ Gap\end{aligned} \quad (1)$$

Table 4. Modified ANOVA for areal surface roughness (Sa) (µm)

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	10.65	1.18	18.84	0
Linear	4	6.61	1.65	26.32	0
Pulse on	1	5.62	5.61	89.45	0
Pulse off	1	0.52	0.52	8.34	0.01
Spark Gap	1	0.38	0.37	6	0.025
Rpm	1	0.09	0.09	1.51	0.237
Square	2	1.28	0.64	10.2	0.001
Pulse on *Pulse on	1	0.38	0.38	6.12	0.024
Pulse off*Pulse off	1	1.11	1.11	17.62	0.001
2-way Interaction	3	2.75	0.92	14.63	0
Pulse on*Pulse off	1	0.67	0.67	10.62	0.005
Pulse on*rpm	1	0.87	0.87	13.88	0.002
Pulse off*Spark Gap	1	1.21	1.21	19.41	0
Error	17	1.068	0.062		
Lack of Fit	15	1.06	0.07	16.96	0.057
Pure Error	2	0.008	0.004		
Total	26	11.72			

4. OPTIMIZATION BY DESIRABILITY ANALYSIS

In the present study, desirability analysis is employed, where the measured properties of each predicted response is transformed to a dimensionless desirability value *d*. The scale of desirability function varies from d=0 to d=1. The desirability analysis optimization was carried out using MINITAB 17 statistical software. Following steps were carried out for the optimization:

i. obtaining the desirability for the response (Sa);
ii. maximizing the desirability and identifying the optimal value

Fig. shows the optimization plot obtained from desirability analysis. Table 5 presents the optimum values obtained from desirability analysis of machining Inconel 825. Table 5 also shows the predicted and experimental values of areal surface roughness (Sa).

Table 5. Optimization results of desirability analysis and experimental validation value for Sa

Optimum input values	Predicted Sa	Experimental validation (Sa)
Pulse on time (Ton) – 10µs Pulse off time (Toff) – 25µs Spark Gap (Ga) – 60µm Rotational speed (rpm) – 90rpm	1.698 µm	2.02 µm

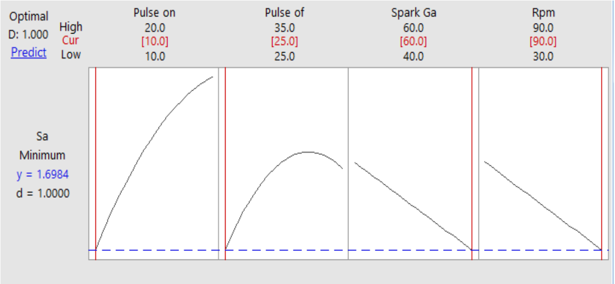

Fig 3. Optimization plot by desirability analysis for Sa

Fig 3. shows the predicted value of Sa with a desirability target value of 1. From fig 3 the optimal operating conditions were determined by maximizing the desirability value d.

5. CONCLUSION

This investigation deals with the 3d parameter of surface roughness viz Sa of Inconel 825 alloy. From this study, it can be observed that areal surface roughness will be more appropriate for evaluating the surface quality and it reflects better nature of surface of the machined parts. The effects of pulse on time, pulse off time, spark gap and rotational speed on areal surface roughness are experimentally investigated.

From the experimental results, pulse on time and pulse off time are found to be most significant effect on areal surface roughness. Spark gap and rotational speed have relatively less significance. A multiple regression equation is determined and presented as eq 1. The modified analysis of variance (ANOVA) for regression analysis indicates that the proposed model for areal surface roughness is significant.

The combination of optimum parameters for the minimum areal surface roughness is obtained by using desirability analysis. From desirability analysis, predicted value of areal surface roughness is obtained as shown in table 5. The validation experiment indicate that it is possible to decrease the areal surface roughness by using the proposed statistical method.

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