Proceedings of 10th International Conference on Precision, Meso, Micro and Nano Engineering (COPEN 10)
December 07 – 09, 2017, Indian Institute of Technology Madras, Chennai – 600 036 INDIA

# Design and Fabrication of Wire Electrical Discharge Turning Setup and Study of Surface Roughness of WEDT Products

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## Abstract

Wire electrical discharge turning (WEDT) is one of the emerging areas, developed to generate cylindrical form on hard and difficult to machine materials. This is achieved by adding an additional axis to WEDM machine. The advantage of using WEDT process for machining difficult to machine materials is the lack of cutting forces and the ability to machine small diameter shafts. In this work, an in house wire electrical discharge turning setup is fabricated and is fixed on the WEDM machine already available. Total runout of the fabricated setup is in the range of 10 to 15 µm. Work material used is Inconel 825. For conducting the experiments, L27 Box-behnken design is chosen. The variation of surface roughness, with variation in Pulse ON time, Pulse OFF time, spark gap and rotational speed are studied. From the experiments conducted, surface roughness values in the range of 2.67 to 3.6 µm were obtained. It is found that the significant factors which affect surface roughness are Pulse ON time and Pulse OFF time. For studying the capabilities of the turning setup, an experiment is conducted to find the least diameter shaft which can be machined. Shafts having diameter in the range of 186 to 190 µm were machined using the setup.

Keywords: EDM, WEDM, WEDT, Inconel 825

## 1. INTRODUCTION

Many advanced materials due to their high hardness, temperature resistance and high strength to weight ratio, are now being used by manufacturing industries for producing automotive components, aerospace components and also for medical applications. Due to high dynamic shear strength, higher strain hardening tendency, and poor thermal diffusivity, machining of these materials using conventional machining process is found to be difficult. Hence non-conventional machining processes are mostly preferred by the researchers. One such machining process is electrical discharge machining. Since the mode of material removal is through melting and evaporation, the hardness of the workpiece becomes irrelevant. One of the major disadvantages with conventional machining is the presence of large cutting forces, which in turn creates residual stresses. This can be overcome by using nonconventional machining processes.

In the case of difficult to machine materials for example nickel alloys like Inconel, the tool life is in the range of 1 to 2 minutes even for ceramic inserts. As the tip of the tool gets worn off easily while machining these alloys, the tool has to be reground every time and this is not desired. In these cases WEDT is preferred as a much better substitute over conventional turning. WEDT is a modified form of WEDM which is used to create cylindrical shaped specimens. In the present work, shafts having diameter in the range of 186 to 190 µm were machined.

Many researchers have contributed to the development of WEDT equipment. Janardhan and Samuel [1] developed a cost effective spindle for WEDT process and concluded that spindle runout was the key parameter affecting consistent machining in WEDT. A pulse classification algorithm for off-line analysis of the WEDT process was developed. Effect of process parameters on MRR, roundness and surface roughness of WEDT specimens were studied. The authors found that surface finish improves with decrease in the number of arc regions per unit time and increase in the average ignition delay time. Qu et al. [2] fabricated a rotary setup and derived a mathematical model for material removal rate of cylindrical wire EDM of free-form surfaces. Maximum material removal rates of 2D wire EDM and cylindrical wire EDM were compared and found that material removal in cylindrical wire EDM is more due to better flushing efficiency. The authors reported that the critical factor in achieving the desired roundness, surface finish, and material removal rate is the spindle error, lesser the spindle error better will be the surface finish. Qu et al. [3] developed a mathematical model for the arithmetic average surface roughness on the ideal surface of a cylindrical wire EDM workpiece. Experiments verified the surface finish model and found that simply adding the roughnesses of 2D wire EDM surfaces and ideal surfaces provided a good estimate of the surface roughness of cylindrical wire EDM parts. Macro ridges, surface craters, recast layers, and heat affected zones were observed, and their sizes were estimated using SEM.

Matoorian et al. [4] studied the effects of intensity, Pulse ON time, voltage, Pulse OFF time, servo, and rotational speed on MRR of WEDT products. The study of the behaviour of the response with the parameters were done using DOE. Haddad and Tehrani [5] studied on the influence of the most relevant cylindrical WEDT factors over MRR. A mixed full factorial design has been selected and DOE and response surface methodology were used to model the response variable taken in the study. The authors reported that the most influential factors which affect MRR were power, voltage, Pulse OFF time, spindle rotation speed and interaction between power and Pulse OFF time. Haddad et al. [6] studied the effect of machining parameters on surface roughness and roundness in cylindrical WEDT of AISI D3 tool steel. The authors found that surface roughness has an increasing trend with increase in voltage and power and decrease in the Pulse OFF time and spindle rotational speed. Cross sections of WEDT parts were examined using SEM and microhardness tests to quantify the sub-surface recast layers and heat affected zones under the specific process parameters. It has also been found that spindle rotational speed, voltage, power and interaction effects between voltage and spindle rotational speed have most significance in case of roundness. Akmal et al. [7] developed a rotary axis mechanism for WEDT and studied the improvement on large length to diameter machining ratio with single pass cutting operation. The



ISBN: 978-93-80689-28-9

authors reported that shafts having diameter in the range of 230 µm were made during the experiments.

## 2. FABRICATION OF WEDT SETUP

Minimising spindle runout is one of the most important factors to be considered during the fabrication of WEDT setup. For this, a smooth and precise base and quality bearings are required. It is important to provide insulation between the spindle and the bearings as an electrical contact would accelerate the wearing of the bearings. Nylon caps were decided to be the insulation material between the bearings and the spindle. From the literature, it was inferred that in order to obtain good surface finish for the turned products the rotational speed of the workpiece must be between 0 to 100 rpm. So a motor needs to be selected with enough torque to rotate the workpiece and at the required rotational speed. A toothed flat belt is selected in order to transmit power from the motor to spindle and to reduce the vibrations if any. The workpiece needs to be connected to the spindle by means of a collet. Collet instead of a chuck was selected to give more holding area to the workpiece and to avoid marks generated by tightening of the chuck. Considering all these factors, an initial design was made in CATIA V5.

Pillow bearing, nylon cap, and the spindle are press fitted together to obtain the bearing assembly which forms the core of the turning setup. One of the key components of the bearing assembly, the nylon cap had to be made to fit in a gap of 1mm (i.e., between the inner surface of bearing and the outer surface of the spindle). An ER-16 straight shank adapter is used as the spindle for the turning setup. Pillow bearing is used to hold the spindle in position and to give free rotation.

The base for the whole setup was made by milling and grinding an 8 inch MS plate to the required dimensions. The bearing assembly and the DC geared motor used to drive the setup are mounted on the base by means of allen bolts. The motor and spindle of bearing assembly are connected by means of a toothed flat belt.

Speed control of DC motor is done by using a pulse width modulation circuit. Arduino Uno R3 microcontroller is used to control the power given to the motor. For providing a DC supply to the motor an SMPS with a 12V DC is used. An acrylic box is made to protect the WEDT setup from dielectric.

The entire setup is fixed on the WEDM ECOCUT machine by means of clamps as shown in Fig. 1. The alignment of the setup is checked with the help of a dial gauge.

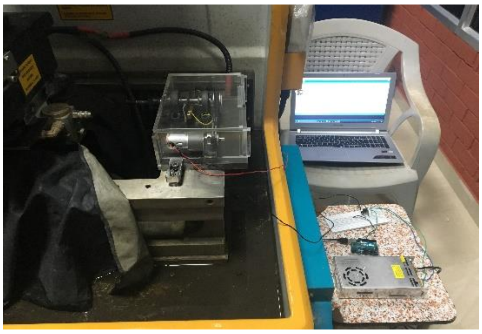

**Fig.1. Setup fixed on WEDM machine**

## 3. EXPERIMENTAL DETAILS

### 3.1. Work piece material

Inconel 825 is a nickel-iron chromium alloy with additions of molybdenum, copper, and titanium. Properties of Inconel 825 is shown in Table 1. It has exceptional resistance against heavily corrosive environments. Chloride ion stress corrosion cracking is prevented by nickel content present in the alloy. Molybdenum present in the alloy helps in resistance against fissures and pitting corrosion. Inconel alloy performs well under sulphuric and phosphoric environments due to the presence of nickel, molybdenum and copper together. Presence of chromium content helps the alloy to resist oxidation. With the right heat treatment, intergranular corrosion can be reduced due to titanium content in the alloy. The ability of Inconel alloy to provide resistance against both point sourced and general corrosion under varying conditions makes the alloy very useful.

**Table 1 Properties of Inconel 825**

| Mechanical Properties | Inconel 825 |
|---|---|
| Density ($g/cm^3$) | 8.14 |
| Melting range (°C) | 1370 - 1400 |
| Yield strength (MPa) | 338 |
| Shear modulus (GPa) | 76 |

### 3.2. Experimental set up

WEDT experiments were conducted on CNC WIRECUT EDM machine, a machine tool supplied by Electronica machine tools Ltd. For measuring the surface roughness, surface roughness tester (MITUTOYO SURFTEST SJ 410) was used. From previous literature it was found that the main factors which affect the machining are Pulse ON time, pulse off time, spark gap and rotational speed. Zinc coated brass wire is used as the tool material for the experiments. The Ra values for all the specimens were measured and the variation of surface roughness with variation in process parameters was studied.

### 3.3. Experimental Design

Four factors and three levels were selected for conducting the experiments. The factors and the levels are given in the Table 2

**Table 2 Factors and their levels**

| Factor | -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 |

L27 box behnken design is chosen for the experimental runs. The reason for choosing box behnken design is to get the curvature effect. Analysis is done in full quadratic model and thus with four factors and three levels, box behnken design fits the model with minimum experimental runs. The runorder for conducting the experiments is generated using Minitab software. All other machining parameters were kept constant during the entire experiments. The constant parameters and their values are given in Table 3.

**Table 3 Constant parameters and their values**

| | |
|---|---|
| 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 |

## 4. WEDT EXPERIMENTS

Aim of this experiment is to find out the smallest diameter shaft that can be machined by this setup. For this a stainless steel shaft of initial diameter 4 mm was chosen.

The machining was done at a feed rate of 3 mm/min for the initial rough cutting to remove the bulk of the material. Fig. 2 shows the stepwise reduction of shaft from the bulk material. The depth of cut was given as 0.2 mm initially and after reducing the diameter to a considerable value, it was changed to 0.1 mm.

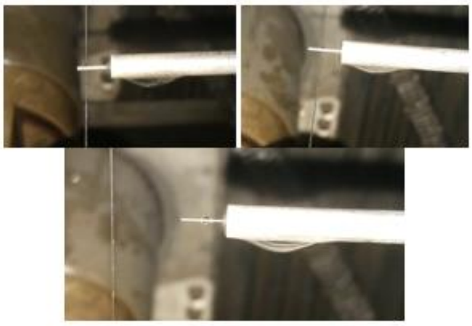

**Fig.2. Stepwise reduction of the shaft from the bulk material**

Trim cuts were done at 1mm/min feed rate and 0.08 mm depth of cut in the final stage. Fig. 3 shows the final shaft obtained.

The diameter of the shaft was measured using OLYMPUS BX 51 metallurgical microscope. Diameter of shaft was measured to be 186.86 µm. Fig. 3 shows the microscopic image of the shaft. From the literature survey, it is seen that the least diameter obtained for brass specimens is 203 µm. For Ti6AI4V least diameter obtained is 230 µm [6].

**Fig.3. Final shaft and Microscopic image of the shaft**

To further explore the capabilities of the setup, a stepped shaft was machined using the setup. Fig. 4 shows the stepped shaft and its microscopic image.

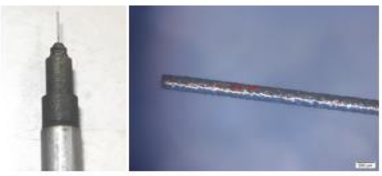

**Fig.4. Stepped shaft and microscopic image of least diameter**

## 5. RESULTS AND DISCUSSIONS

### 5.1. Results

Experiments are conducted on Inconel 825 specimens and the surface roughness values are measured.

**Fig.5. Turned specimens**

Fig. 5 shows few of the specimens from the 27 experiments. Table 4 shows the result of the experiments.

**Table 4 Result of the experiments**

| Run Order | Pulse ON (µs) | Pulse OFF (µs) | Spark Gap (µm) | Rotational speed (rpm) | Surface roughness (µm) |
|---|---|---|---|---|---|
| 1 | 15 | 30 | 60 | 90 | 2.7290 |
| 2 | 10 | 35 | 50 | 60 | 2.1920 |
| 3 | 15 | 35 | 50 | 90 | 2.6770 |
| 4 | 15 | 35 | 60 | 60 | 2.9444 |
| 5 | 15 | 30 | 60 | 30 | 2.7870 |
| 6 | 10 | 30 | 60 | 60 | 2.4630 |
| 7 | 10 | 30 | 50 | 30 | 2.5700 |
| 8 | 15 | 30 | 40 | 90 | 2.9880 |
| 9 | 15 | 30 | 50 | 60 | 2.9300 |
| 10 | 15 | 30 | 40 | 30 | 2.5840 |
| 11 | 20 | 25 | 50 | 60 | 3.0260 |
| 12 | 15 | 25 | 40 | 60 | 2.6743 |
| 13 | 20 | 35 | 50 | 60 | 3.6060 |
| 14 | 15 | 35 | 50 | 30 | 3.1060 |
| 15 | 15 | 35 | 40 | 60 | 3.0658 |
| 16 | 15 | 25 | 50 | 90 | 2.9610 |
| 17 | 15 | 30 | 50 | 60 | 2.8530 |
| 18 | 15 | 25 | 50 | 30 | 2.4200 |
| 19 | 10 | 30 | 50 | 90 | 2.3560 |
| 20 | 15 | 25 | 60 | 60 | 2.8771 |
| 21 | 20 | 30 | 40 | 60 | 3.1620 |
| 22 | 20 | 30 | 60 | 60 | 3.3120 |
| 23 | 20 | 30 | 50 | 30 | 3.2330 |
| 24 | 10 | 30 | 40 | 60 | 2.2630 |
| 25 | 15 | 30 | 50 | 60 | 2.9370 |
| 26 | 10 | 25 | 50 | 60 | 2.3317 |
| 27 | 20 | 30 | 50 | 90 | 3.5870 |

### 5.2 ANOVA for surface roughness

Analysis of variance was done in order to find out the significant factors that affect surface roughness. The factors having P value less than 0.05 are significant. Here Pulse ON time, Pulse OFF time and an interaction between Pulse ON and rotational speed are significant. Lack of fit value of 0.15 indicates that it is not significant. An improved model has been created using Minitab software by eliminating insignificant factors. Table 5 shows the results of modified ANOVA.

**Table 5 Modified ANOVA for surface roughness**

| Source | df | Adj SS | Adj MS | F value | P value |
|---|---|---|---|---|---|
| Model | 8 | 3.436 | 0.429 | 42.22 | 0.000 |
| Pulse ON | 1 | 2.755 | 2.755 | 270.77 | 0.000 |
| Pulse OFF | 1 | 0.141 | 0.141 | 13.86 | 0.002 |
| Spark Gap | 1 | 0.011 | 0.011 | 1.15 | 0.297 |
| Rotational speed | 1 | 0.029 | 0.029 | 2.93 | 0.104 |
| Pulse ON x Pulse OFF | 1 | 0.129 | 0.129 | 12.72 | 0.002 |
| Pulse ON x Rotational speed | 1 | 0.080 | 0.080 | 7.93 | 0.011 |
| Pulse OFF x Rotational speed | 1 | 0.235 | 0.235 | 23.11 | 0.000 |
| Spark gap x Rotational speed | 1 | 0.053 | 0.053 | 5.24 | 0.034 |
| Lack of fit | 16 | 0.178 | 0.011 | 5.15 | 0.175 |
| Error | 2 | 0.004 | 0.002 | | |
| Total | 26 | 3.620 | | | |

Table 6 gives the R-squared value for surface roughness. The "Pred. R-Squared" of 78.86 % is in reasonable agreement with the "Adj. R-Squared" of 91.8 %; i.e. the difference is less than 20 %.

**Table 6 R - squared values for surface roughness**

| | |
|---|---|
| R - squared | 96.26 % |
| Adj. R - squared | 91.8 % |
| Pred. R - squared | 78.86 % |

Regression equation in terms of factors:

$R_a$ = 0.52 - 0.1769 Pulse ON + 0.0107 Pulse OFF + 0.0262 Spark gap + 0.0552 Rotational speed + 0.00720 (Pulse ON x Pulse OFF) + 0.000947 (Pulse ON x Rotational speed) - 0.001617 (Pulse OFF x Rotational speed) - 0.000385 (Spark gap x Rotational speed)

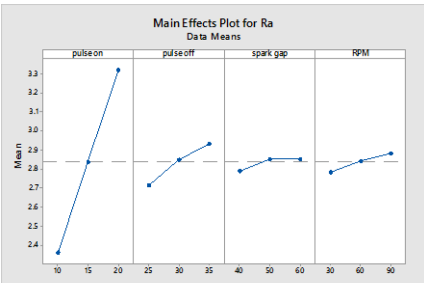


**Fig.6. Main effects plot for surface roughness**

From the main effects plot shown in Fig. 6, it can be seen that the surface roughness is increasing linearly with the Pulse ON time. Larger the Pulse ON time larger would be the energy of the spark being generated this would create larger craters thus making the surface more rough. Since the workpiece is in constant motion while doing WEDT, with increase in pulse off time some areas will be left unexposed to the spark. This creates some areas with crater and some without crater thus increasing the surface roughness. The spark gap seems to have less effect on the surface roughness of the WEDT products. One reason for increase in the surface roughness during increase in spark gap could be due to the reduced number of sparks and thus spark regions due to increase in resistance. If the spark gap is minimum the breakdown of the dielectric happens faster and thus there would be more sparks. Since there is lesser sparks the region will not be uniform and hence the increase in surface roughness. From the main effects plot it can be seen that the surface roughness variation with respect to change in rotational speed is considerably low. Thus it doesn't affect the surface roughness much. The slight increase in surface roughness can be due to the fact that some regions might not be properly exposed to the spark due to increase in surface velocity.

## 6. CONCLUSIONS

Development of a rotary setup for WEDM machine which can generate cylindrical forms on hard to machine materials is done. Surface roughness of products machined through this process is studied and process parameters which affect it are found.

- WEDT setup with an overall run out of 10 to 15 µm was fabricated and turning was done with that equipment.
- Shaft having 186.86 µm in diameter have been made using the WEDT setup.
- The variation of surface roughness, with variation in Pulse ON time, Pulse OFF time, spark gap and rotational speed are studied.
- It was observed that the significant factors which affects the surface roughness are Pulse OFF time and Pulse ON time. As Pulse ON time increases, the surface roughness value also increases.
- Pulse on time has the most significant effect on MRR but the detailed study of the effects of process parameters on MRR is to be studied further.

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