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Investigation on Forming of Small Cylindrical Geometries in Electrolytic Tough Pitch Copper by Wire Electrical Discharge Turning Process

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Abstract

This paper presents an experimental investigation in developing small cylindrical pins in electrolytic tough pitch copper (ETP Cu) material using non-conventional machining process e.g. wire electrical discharge turning (WEDT). The material ETP Cu is soft in nature and has growing range of application in the field of aerospace & electronics industries for advanced applications. In conventional machining process, it is difficult to machine the miniature parts in ETP Cu because of frequent formation of build-up edge at cutting tool tip and the tendency of the part getting bend due to the presence of tool pressure. In the present investigation, a rotary axis has been added to five-axis CNC wire electrical discharge machine (WEDM) to develop the pins of 0.5 mm diameter with 15 mm length which is very difficult to fabricate using either a conventional or a CNC lathe. The developed pins can be used for precise biasing of the microwave oscillator and as an electrode for generating precision small holes by electrical discharge machining (EDM) process. Response surface methodology (RSM) with central composite design has been used for planning and designing the experiments. Under this investigation, finally 31 numbers of experiments have been carried out to study the effect of controllable process variables, i.e. pulse on time, pulse off time, servo voltage and spindle speed on machining response, i.e. circularity error of the machined pins. Also it is observed that for circularity error, pulse on time is the most dominating factor compare to others process variables.

Keywords: WEDM, WEDT, ETP Cu, RSM.

1. INTRODUCTION

In wire EDM, a thin single-strand of metal wire, generally made of brass material is fed through a work piece that is submerged in a tank of dielectric fluid. The wire electrode is constantly fed from a spool through different stage of wire guides to maintain the wire tension to a desire level. Finally the wire, is fed from upper guide to lower guide through the work piece to generate components with intricate shapes and profiles with very small inner corner radii of size half of the diameter of the wire used. Wire electrical discharge turning is another innovative concept of non-traditional machining process where a rotary axis is added with the WEDM. This process is capable for machining different types of cylindrical forms like straight, tapered and stepped on hard and difficult to machine material, as well as the miniature cylindrical parts with comparatively long length in soft material because those are very difficult to machining in the conventional machining process.

Several researchers have developed the concept of wire electrical discharge turning process. Haddada and Tehrani studied roundness on the cylindrical wire electrical discharge turning (CWEDT) on AISI D3 tool steel material and suggested to do full factorial design in DOE technique to determine a working space with high robustness and then use regression analysis to generate a model of high stability [1]. A pulse classification algorithm for off-line analysis of the WEDT process was developed by using MATLAB and the author observed that the roundness error of the WEDT components are influenced by the occurrence of arc regions, width of arc and the roundness error can be reduced by 74% by reducing the pulse off time [2]. Ki Young Song et al. developed the EDM turning using a conductive strip electrode and it was fed continuously in place of wire of the WEDM process with different attachment and author mentioned that it increased the material removal rate because of its large machining area and non-breaking electrode [3]. Hadad investigated the effects of machining parameters on roundness in the cylindrical wire electrical discharge turning (CWEDT) of AISI D3 Tool Steel and reported that the voltage and spindle rotational speed were more important than the power for controlling the roundness [4]. A new technique by combining wire electrical discharge turning and ultrasonic vibration was introduced to evaluate material removal rate and concluded the higher MRR gained by the employment of ultrasonic vibration is mainly attributed to reduction of friction between the wire and the wire guide that causing reduction of wire breakage [5]. The confirmation tests indicate that it is possible to decrease the roundness significantly by using the proposed statistical technique and reported the roundness is decreased by 1.33 times [6]. A precise, flexible and corrosion-resistant underwater rotary spindle to carry out the experiments and it was reported by the author that the spindle was found to be a critical factor in achieving the desired roundness [7].

After a comprehensive study of the existing literature, it is noticed that till now no work is reported on soft material like ETP Cu. Therefore, the aim of the present investigation is to form smallest cylindrical parts with long length by WEDT process on ETP Cu material.

2. EXPERIMENTAL PROCESS

In present work, first necessary pilot experiments were carried out to estimate the range of four variable process parameters and then finally 31 experiments were conducted in a particular sequence in five-axis, submerged type WEDM machine (Fanuc, Alpha-0iD) to understand the effect of process parameters on performance parameters like circularity error using response surface methodology(RSM). Electrolytic tough pitch copper (99.90% copper and 0.04% Oxygen) of grade C11000 has been used as a work material which is hard drawn bus bar with high

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thermal and electrical conductivity, good resistance and tampering. This material is suitable for soldering and brazing also. The rod of size (Ø2mm x 25mm long) has been used as an input specimen which is fabricated form the ETP Cu bar using WEDM process.

The error of circularity is defined as the radial distance between the minimum circumscribing circle and maximum inscribing circle, which contain the profile of the surface at a section perpendicular to the axis of rotation. After fabrication of all the specimens by WEDT process shown in Fig. 1. The circularity error of each of the machined components is measured by the roundness measurement instrument (Make: Taylor Hobson, Model: Talyrond 585) shown in Fig. 2

Fig. 1. Few fabricated specimens by WEDT process

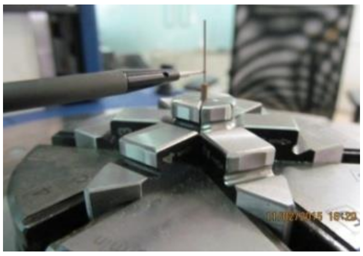

Fig. 2. Circularity error measurement setup

3. EXPERIMENTAL RESULTS AND ANALYSIS

In the statistical design of experiments, the response surface methodology (RSM) is a collection of mathematical and statistical techniques useful for the modelling and analysis of experimental findings. The most extensive application of RSM is in the particular situations where several input variables influence some performance measure or quality characteristic is known as the response.

The scheme under RSM has been developed for carrying out experiments to investigate the effect of process parameters on the output parameters. The process variables and their ranges have been generated for carrying out the successful experiment which is shown in Table 1. The maximum and minimum range of process parameters have been selected based on the pilot experiments.

Table 1: Process parameters and their levels

Parameters	Level				
	(-2)	(-1)	0	(+1)	(+2)
Pulse off time (T_{off}) (µs)	30	32	34	36	38
Pulse on time (T_{on}) (µs)	6	7	8	9	10
Spindle speed (SS) (rpm)	930	1005	1080	1155	1230
Servo voltage (SV) (volt)	70	72	74	76	78

Fixed factors which are non-variable in nature have been set apart from the experiment and they are neither presumed to have an effect on the process [1]

Wire tension (machine unit)	: 1700
Flow rate (machine unit)	: 1
Depth of cut (mm)	: 0.1(rough), 0.05(finish)
Specimen material	: ETP Copper (C11000)
Size of the specimen (mm)	: Diameter: 2, length: 25
Machining length (mm)	: 15

The coded values of process parameters setting and their corresponding measured responses are mentioned in Table 2.

Table 2: Process parameters setting and measured response

Run Order	Coded values				Response
	T_{off}	T_{on}	SS	SV	Circularity error (µm)
1	-1	-1	-1	-1	16.38
2	1	-1	-1	-1	15.87
3	-1	1	-1	-1	13.19
4	1	1	-1	-1	12.58
5	-1	-1	1	-1	14.27
6	1	-1	1	-1	13.97
7	-1	1	1	-1	13.92
8	1	1	1	-1	13.22
9	-1	-1	-1	1	16.86
10	1	-1	-1	1	16.11
11	-1	1	-1	1	13.52
12	1	1	-1	1	13.17
13	-1	-1	1	1	14.38
14	1	-1	1	1	13.72
15	-1	1	1	1	13.96
16	1	1	1	1	13.51
17	-2	0	0	0	15.29
18	2	0	0	0	14.12
19	0	-2	0	0	16.53
20	0	2	0	0	12.95
21	0	0	-2	0	15.84
22	0	0	2	0	13.99
23	0	0	0	-2	11.61
24	0	0	0	2	12.28
25	0	0	0	0	12.27
26	0	0	0	0	12.69
27	0	0	0	0	12.56
28	0	0	0	0	12.43
29	0	0	0	0	12.37
30	0	0	0	0	12.63
31	0	0	0	0	12.39

The parameter circularity error has been considered as the output parameters to estimate the quality of fabrication achieved by this WEDT process. The regression equations have been developed using all experimental data and have been plotted meticulously to investigate the effect of process variables on various response characteristics. The analysis of variance (ANOVA) has been performed to analyze all the results statistically. A second order model of circularity error has been developed. The linear relationship between factors and factors effects and circularity error (response) is represented in Equation (1).

$$\text{Circularity Error} = 292.5 - 10.01\,A - 21.86\,B - 0.2845\,C + 3.73\,D + 0.14776\,A^2 + 0.5998\,B^2 + 0.000114\,C^2 - 0.02089D^2 + 0.007\,A*B + 0.000001\,A*C - 0.0033\,A*D + 0.009089\,B*C + 0.0176\,B*D - 0.000558\,C*D \quad (1)$$

(Where A: pulse off time, B: pulse on time, C: spindle rotational speed, D: servo voltage)

The p-value of different process parameters, square effect of parameters and interaction between parameters are shown in Table 3. It has been observed that pulse off time, pulse on time, spindle speed, servo voltage, square effect of pulse off time, pulse on time, spindle speed, servo voltage and interaction effect between pulse on time and spindle speed, between spindle speed and servo voltage significantly influence circularity error as the p-value of each of them are less than 0.05.

Table 3: P-value of parameters on responses

Term	Response
	Circularity error
Constant	0.000
Pulse off time	0.000
Pulse on time	0.000
Spindle Speed	0.000
Servo Voltage	0.003
Pulse off time*Pulse off time	0.000
Pulse on time*Pulse on time	0.000
Spindle Speed*Spindle Speed	0.000
Servo Voltage*Servo Voltage	0.021
Pulse off time*Pulse on time	0.752
Pulse off time*Spindle Speed	0.997
Pulse off time*Servo Voltage	0.769
Pulse on time*Spindle Speed	0.000
Pulse on time*Servo Voltage	0.433
Spindle Speed*Servo Voltage	0.074

The value of S, R-Sq and R-Sq (adj) of the regression analysis of the circularity error is shown in Table 4. It has been observed that the s-value of the responses is smaller and R-Sq and R-Sq (adj) values of the responses are comparatively high. Reference to this it can be concluded that the data for each response are well fitted in the developed models. Analysis of variance (ANOVA) and subsequently F-value and p-value tests have been carried out to test the adequacy of the developed mathematical models for the responses to form smallest cylindrical parts with long length in ETP Cu by wire electrical discharge turning process.

Table 4: S, R-Sq and R-Sq (adj) values of responses

Responses	S-value	R-Sq value (%)	R-Sq (adj) value (%)
Circularity error	0.17500	99.22	98.54

The Table 5 shows the results of analysis of variance for response, p-value of the source of regression model and linear effects are much lower than 0.05 for this response. The developed second order regression model for this response is significant. Also it is observed that for circularity error, pulse on time (37.37%) is the most dominating factor followed by spindle speed (32.7%), pulse off time (27.5%) and servo voltage (2.4%)

Table 5: Results of analysis of variance for circularity error

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	14	62.32	4.45	145.32	0.000
Linear	4	10.80	2.70	88.11	0.000
T_{off}	1	2.80	2.80	91.44	0.000
T_{on}	1	3.80	3.80	124.27	0.000
SS	1	3.33	3.30	108.74	0.000
SV	1	0.245	0.245	8.01	0.000
Square	4	28.27	7.07	230.77	0.012
Interaction	6	7.57	1.26	41.21	0.004
Error	16	0.49	0.030	-	-
Lack-of-Fit	10	0.35	0.035	1.52	0.314
Pure Error	6	0.14	0.023	-	-
Total	30				

4. PARAMETRIC ANALYSIS

The combined effect of spindle speed and servo voltage on circularity error is shown in Fig. 3. Pulse off time and pulse on time are taken as constant at 34μs and 8μs respectively. It is observed that circularity error first increases and then decreases following a parabolic curve with change in spindle speed. Because in low spindle speed, spindle run-out effect is more compare to moderate spindle speed which affect the circularity of the job to be turned. It can be clearly seen that in the higher values of spindle speed by increasing the voltage values, the circularity error value increases [4].

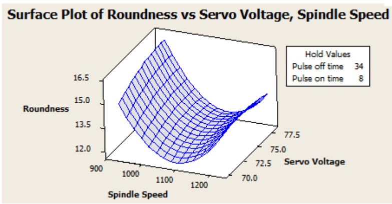

Fig.3. Estimated response surface of circularity error vs. SS & SV

Fig. 4 shows the estimated response surface of circularity error in function of the factors of pulse on time and spindle speed, whilst the pulse off time and servo voltage remain constant at 34μs and 74volt respectively. It can be observed that decreasing pulse on time and decreasing spindle speed, circularity error increases. But in the higher value of pulse on time and lower value of spindle speed, the circularity error is decreasing. It can also be clearly seen that circularity error decreases with the increase of spindle speed with lower pulse on time [2].

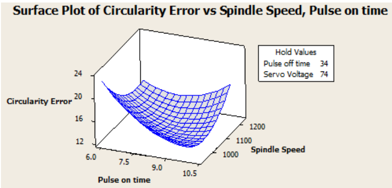

Fig.4. Estimated response surface of circularity error vs. SS & T_{on}

Fig. 5 shows the optimization result for the minimum circularity error on the developed mathematical model using Equation (1). To minimize the response, equal importance has been placed on the higher, target and on the lower bound of the linear desirability function. For linear desirability function (D), the value of the weight is considered as 1. Using the MINITAB software, the minimum circularity error has been optimized which is shown to be 11.444µm when the pulse off time, pulse on time, spindle speed and servo voltage are set at their optimal parametric setting of 34µs, 9µs, 1055rpm and 70volt respectively. The highly effective parameters on the roundness have been found as pulse on time, spindle rotational speed and pulse off time, whereas servo voltage has less effective factor.

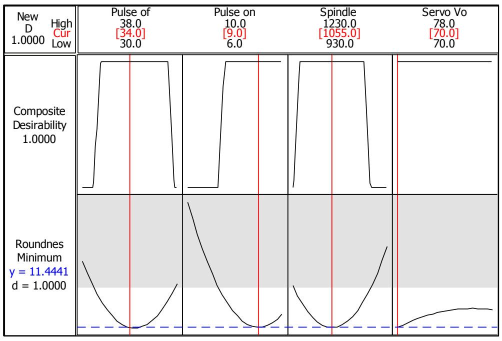

Fig.5. Optimization result of minimum circularity error

5. FINAL VARIFICATION OF THE EXPERIMENT

To verify the proposed mathematical model, set of experiments have been carried out according to the parameter settings obtained from the optimization results for minimum circularity error. These experiment results have been compared with the predicted optimum results, the experimental results and the predicted optimal results along with the predication errors have been shown in Table 6.

Table 6: Confirmation test of circularity error

Responses	Parameter settings	Exp. results (µm)	Predicted results (µm)	Percent error in prediction
Circularity Error	T_{off} : 34µs, T_{on} : 9µs, SS: 1055rpm, SV: 70volt	11.63	11.44	1.63

It has been observed that predicted values are quite close to the experimental results. These small prediction errors have been occurred may be due to inherent inaccuracy in setting of the customized rotary table setup during operation and the measurements of circularity error using roundness measuring instrument. Actually the predicted value of circularity error is 11.44µm and experimental value of circularity error is 11.63µm and the involved error is 1.63%. So the developed model can be useful in predicting output circularity error with an error of 5.0% for any parameter combination within the limits of range taken in the analysis.

6. CONCLUSIONS

In the present work, the small cylindrical pin of diameter 0.5mm with 15mm length has been fabricated using wire electrical discharge turning (WEDT) process on electrolytic tough pitch copper (ETP Cu) material. In this process mathematical model has been developed for circularity error by using response surface methodology (RSM) and finally experimentation has been carried out to identify the effect of process parameters on performance parameters. It has been noticed that spindle speed and pulse on time are the dominant parameters for circularity error. The optimum value of circularity error has been calculated at moderate value of pulse off time and spindle speed, higher value of pulse on time and lower value of servo voltage.

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