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Prediction of Angular Error and Surface Roughness in Wire-EDM Taper cutting of AISI D2 Tool Steel

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Abstract

The wire electrical discharge machining (WEDM) process is a non-traditional method which is widely used in the manufacturing of high-hardness steel precision tooling. Taper-cutting is one of the most important application of wire EDM process used for producing precise complex geometries with inclined surfaces in hard material parts and it is particularly significant in the manufacturing of tooling that requires draft angles. During taper cutting operation the wire is subjected to deformation leading to deviations in the angular dimensions and loss of tolerances in machined parts. As a result, the machined part losses its precision. In the present paper, experiments were conducted in order to find the effect of process parameters such as taper angle, pulse on time and pulse off time on response variables such as surface roughness and angular error by WEDM taper cutting on AISI D2 tool steel using statistical design of experiments. The experiments were designed using Response Surface Methodology (RSM) – Central Composite design (CCD) involving three variables with five levels. An attempt has been made to develop regression model for relating the responses to the process parameters. Separate analysis of variance (ANOVA) is used to analyze the effect of parameters and contribution of each parameter affecting the responses is calculated. Results show that taper angle is the most significant parameter affecting angular error and pulse off time is *the most significant parameter affecting surface roughness.*

Keywords:— *Wire EDM, Taper Cutting, Surface Roughness, Angular Error, Response Surface Methodology*

I. Introduction

Wire electrical discharge machining (WEDM) is among the more widely known and applied non-traditional machining processes in industry today which demands high-speed cutting and high-precision machining to realize productivity and improved accuracy for manufacturing geometrically complex and hard material parts that are extremely difficult to machine by the main stream machining processes. It is a thermo- electrical process in which the material is eroded by a series of sparks between the work piece and the wire electrode (tool). Wire electro discharge machining (WEDM) has become one of the most popular processes for producing precise geometries in hard materials, such as those used in the tooling industry. The so -called taper cutting involves the generation of inclined ruled surfaces, and it is especially important in the manufacturing of tooling requiring draft angles [1].

The wire is kept vertical when vertical cuts are required in the work piece but in the case of taper-cutting the wire is made inclined by displacing upper and lower guides of wire with respect to the vertical as shown in figure 1. The wire deviation from its programmed shape occurs because the wire possesses a certain stiffness value and the angle β represents angular error induced by this effect. In order to understand the problem of the loss of precision in taper-cutting, figure 1 shows the deformation of the wire when applying the relative displacement between the guides. If the wire had no stiffness, it would exactly adapt to the geometry of the guide. In this ideal case, the programmed angle would be α, this is the angle expected in the machined part. However, the fact that the wire has a certain value of stiffness is the reason for the deviation of the wire with respect to its ideal shape and the angle β represents the angular error induced by this effect. The value of the error depends on aspects such as the distance between upper and lower guides, the stiffness of the wire, the geometry of the guides and the forces exerted during the cutting process, amongst other factors. As a final consequence, tolerances are lost in parts machined using this operation [5].

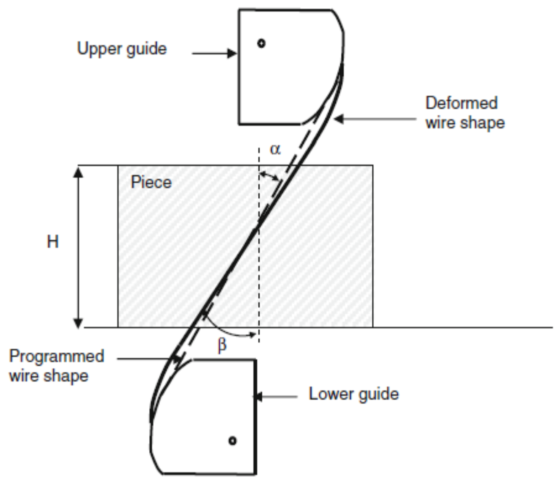

Figure 1: Theoretical and actual location of the deformed wire [9]

II. Literature Review

The term taper-cutting is commonly used for WEDM operations aiming at generating parts with tapered profiles which is one of the most important applications of WEDM process. Kinoshita et al. [2] initially proposed the problem of taper cutting by developing a linear model for wire deformation without considering the forces acting during the process. The variation of the geometrical inaccuracy caused due to wire lag phenomenon with various machine control parameters in machining of die steel using WEDM has been investigated by Puri and Bhattacharyya [4]. An attempt to study the in-process static mechanical behaviour of the wire had been carried out by Dauw and Beltrami [5]. Theoretical model and inclined discharge angle concept for material removal analysis of tapering process in WEDM was developed and to improve the efficiency of the process a strategy including control of wire tension and discharge power was proposed by Huse and Su [6]. Sanchez et al. [7] presented computer simulation software for the analysis of error in wire EDM taper-cutting. An on line adjustment of axial force exerted by the machine on the wire in WEDM taper cutting was carried out by Chiu et al. [8]. Puri and Bhattacharyya [9] investigated the effect of wire vibration in WEDM. It was reported that the variable nature of various forces acting along or upon the wire leads to wire vibration.

Literature review reveals that the researchers have focused on straight cutting with little attention paid to taper cutting in WEDM. Hence the present work is focused on investigating the effect of various process parameters such as taper angle, pulse on time and pulse off time on responses such as angular error (AE) and surface roughness (SR) in WEDM taper cutting on AISI D2 tool steel using design of experiments.

Table 1: Chemical Composition of AISI D2 Tool Steel

Element	C	Si	Mn	S	P	Cr	M	N
Weight %	1.60	0.72	0.51	0.025	0.041	12.05	0.61	0.35

Table 2: Coded and actual levels of process parameters

Machining Parameters	Units	Levels				
		-1.682	-1	0	+1	+1.682
Taper Angle (A)	°	4	6	9	12	14
Pulse on Time (B)	µs	112	115	120	125	128
Pulse off (C)	µs	51	53	56	59	61

Table 3: Controllable Process

Parameter	Symbol	Units	Value
Thickness	t	mm	40
Servo Voltage	(SV)	volts	10
Water Pressure	WP	Kg/cm2	10
Wire Tension	WT	gms	8
Wire Feed	WF	m/min	2

Table 4: Experimental Plan & Summary of Results

Std. order	Coded factors			Actual factors			AE degrees	SR µm
	Taper Angle (A)- °	Pulse on Time (B)-µs	Pulse off (C) - µs	Taper Angle (A)- °	Pulse on Time (B)-µs	Pulse off (C)- µs		
1	-1	-1	-1	6	115	52	0.19	3.06
2	1	-1	-1	12	115	52	0.35	2.71
3	-1	1	-1	6	125	52	0.16	2.9
4	1	1	-1	12	125	52	0.42	2.25
5	-1	-1	1	6	115	58	0.22	3.22
6	1	-1	1	12	115	58	0.25	3.95
7	-1	1	1	6	125	58	0.03	2.78
8	1	1	1	12	125	58	0.41	3.02
9	-1.682	0	0	3.95	120	55	0.14	2.69
10	1.682	0	0	14.04	120	55	0.39	2.94
11	0	-1.682	0	9	112	55	0.31	3.14
12	0	1.682	0	9	128.4	55	0.33	2.87
13	0	0	-1.682	9	120	49.95	0.28	2.86
14	0	0	1.682	9	120	60.04	0.26	3.41
15	0	0	0	9	120	55	0.27	1.98
16	0	0	0	9	120	55	0.25	1.76
17	0	0	0	9	120	55	0.32	1.96
18	0	0	0	9	120	55	0.23	1.56
19	0	0	0	9	120	55	0.24	1.48
20	0	0	0	9	120	55	0.29	1.56

III. Experimentation

Experiments were carried out on Electronica Sprintcut WEDM and brass wire of 0.25 mm diameter was used in the experiments. Deionised water was used as a dielectric medium. AISI D2 tool steel has been chosen as work piece material whose composition is shown in Table.1.

The work pieces of 20 numbers were prepared by cutting into square sizes of thickness (t) 40mm each respectively with 10mm width (w) and then grounded in order to get good finish. The lower and upper surfaces of the work parts are grounded as they can be used as a reference for measurement of the angle. Angular error (AE) and Surface roughness were considered as the two important output performance measures for optimizing machining parameters of WEDM taper cutting process. Angular measurements have been carried out on a Zeiss Prismo-5 model CNC Coordinate Measuring Machine. The

Surface roughness values ware measured by Mitutoyo surf test SJ-301. Two level full factorial design with 6 central runs and 6 axial runs leading to central composite rotatable design was used to conduct experiments. Coded and actual levels of various process parameters are presented in Table 2. Controllable process parameters available are shown in Table 3. The experimental plan and summary of results are given in Table 4.**Table 2**: Coded and actual levels of process parameters

IV. RSM Analysis

Response surface regression analysis is done to evaluate the effect of individual parameter and their interactions on response parameters viz. angular error (AE) and surface roughness (SR) using Stat-Ease Design Expert software.

4.1. Angular Error

The analysis of variance (ANOVA) of this model for angular error is conducted after neglecting contribution of all the insignificant model terms. The model F-Value of 21.72 implies that the model is significant. There is only a 0.01% chance that this large "Model F-Value" could occur due to noise. In this case A and AB are significant model terms. The final equation in terms of actual values are given as

$$A\ Error = 4.269 - 0.410 * A - 0.032 * B - 0.0063 * C + 0.0036 * A*B \quad \ldots\ldots 1$$

4.2. Surface Roughness

Based on lack of fit test, quadratic model is selected. After dropping insignificant terms, the reduced model of ANOVA for surface roughness is conducted. The model F-value of 23.30 implies that the model is significant. There is only a 0.01% chance that this large "Model F- Value" could occur due to noise. Value of "Prob>F" less than 0.0500 indicates model terms are significant. In this case B, C, AC and A_2 are significant model terms. The final equation in terms of coded factors and actual values are given as

$$SR = 402.458-(1.404*TA)-(3.955*Ton)-(5.606*Toff)-(0.006*TA*Ton)+(0.027*TA*Toff)-(0.006*Ton*Toff)+(0.036*TA^2)+(0.018*Ton^2)+(0.055*Toff^2) \quad \ldots\ldots 2$$

V. Results and Discussion

Based on response surface model after regression analysis, the results in terms of effect of taper angle, pulse on time and pulse off time on angular error and cutting speed are calculated and discussed in the following sections.

5.1 Angular Error (AE)

5.1.1. Effect of taper angle on AE

Subsequent Figure 5 explains about effect of Taper angle on Angular error, there is an increase in angular error upon increase in taper angle with respect to the pulse on time. It can be observed from the graph that as the taper angle increases angular error increases and also observed that work piece with higher pulse on time (Pulse on Time=125) having more angular error compare with work piece with lower pulse on time (Pulse on Time=115).

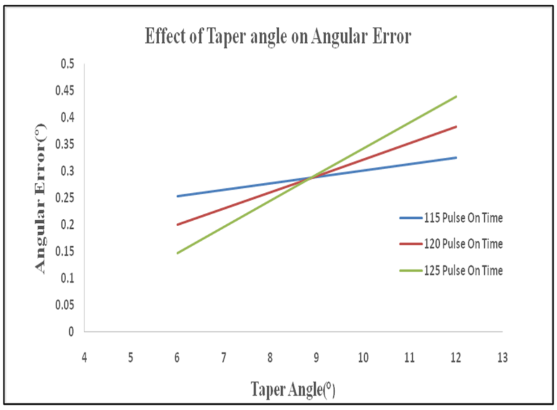

Figure 2: Effect of taper angle on angular error

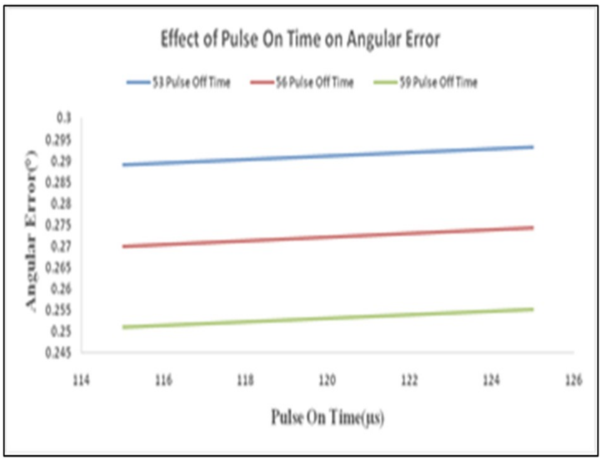

Figure 3: Effect of pulse on time on angular error

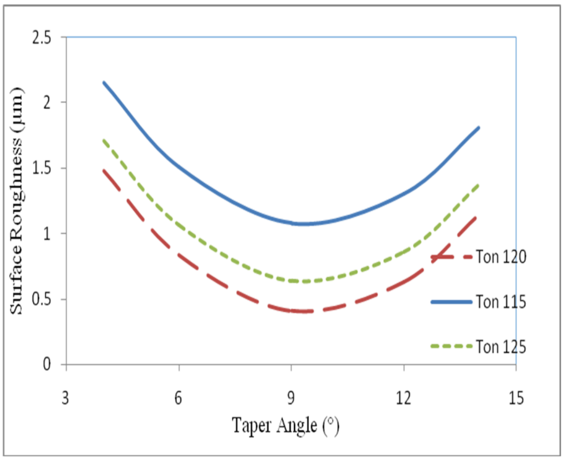

Figure 5: Effect of taper Angle on surface roughness

5.1.2. Effect of pulse on time on AE

From Figure 6 it can be observed that the increase in pulse on time leads to increase in angular error for various levels of pulse off time. As the pulse on time increases more material gets melted at the tool work piece inter face and due to lack of proper flushing surface irregularities may occur which leads to angular error. It is also observed that the angular error is more for the work piece with less pulse off time (Pulse off time=53) compared to the work piece with more Pulse off time (Pulse off time =59) because as the pulse of times are less there is not enough time for the flushing to clear the debris between the tool and the work piece.

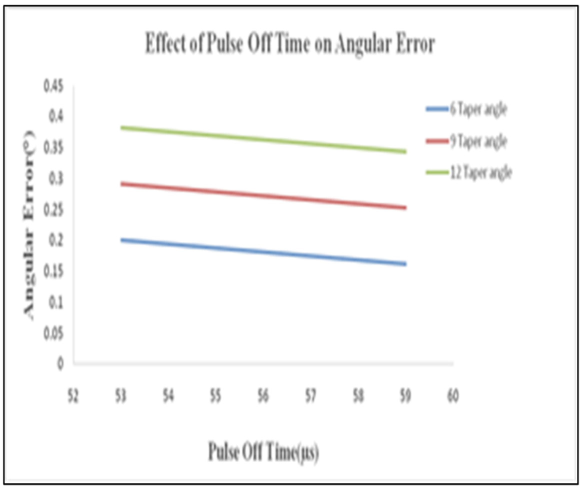

Figure 4: Effect of pulse off time on angular error

5.1.3. Effect of pulse off time on AE

Figure implies that with the increase in pulse off time the angular error gradually decreases at various taper angles. It can also be observed that the angular error is more for the work piece with higher taper angle (Taper angle=12) compared to the work piece with lower taper angle (Taper angle=6). As the pulse off time increases, flushing time between tool and work piece inter face increases which results in decrease in the angular error.

5.2 Surface Roughness (SR)

5.2.1. Effect of taper angle on SR

Subsequent Figure 5 depicts the effect of taper angle on surface roughness with respect to various pulse on times. It is observed that as the taper angle increases the displacement between the guides and the contact between the wire and guide also increases and the influence of the axial force acting on the wire in the zone of cutting increases resulting lower surface roughness up to an optimum value and increase then. It is observed that with respect to pulse on time for the increase in taper angle the surface roughness values are initially at high, proceeding to low then high. The stiffness of the wire and the forces exerted during the cutting process are the reasons leading to increase in surface roughness with increase in taper angle. It is observed that the taper angle has less effect on surface roughness.

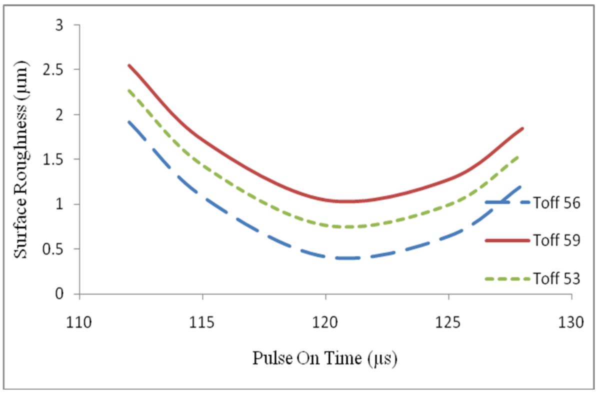

Figure 6: Effect of pulse on time on surface roughness

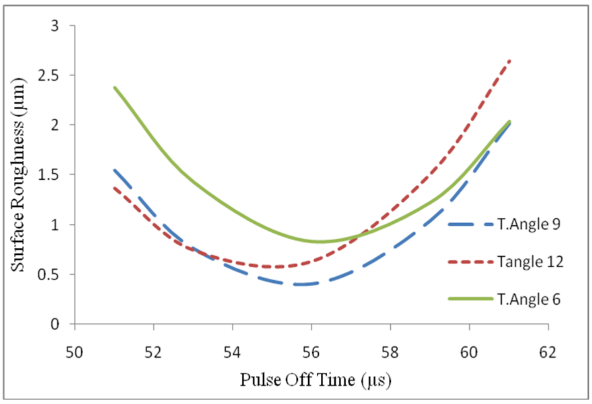

Figure 7: Effect of pulse off time on surface roughness

5.2.2. Effect of pulse on time on SR

From Figure 6 it can be seen that the surface roughness decreases with the increase in pulse on time initially upto 120µs of pulse on time and then increased with respect to various taper angles. As the pulse on time increases more material gets melted at the tool work piece inter face and due to lack of proper flushing surface irregularities may occur which leads to surface roughness.

5.2.3. Effect of pulse off time on SR

Figure 7 shows the effect of pulse off time on surface roughness with respect to different taper angles. It is observed that as the surface roughness decreased slowly initially at lower pulse off times and gradually increased with the increase in pulse off times. The increase in pulse off time provides better flushing off debris take place from the inter electrode gap resulting in decrease in surface roughness but due to the influence of higher taper angles surface roughness increases.

IV. CONCLUSIONS

Based on response surface model after regression analysis, the results in terms of effect of taper angle, pulse on time & pulse off time on angular error and surface roughness are concluded as.

- Increase in taper angle leads to sharp increase in angular error indicates that taper angle is most significant parameter affecting the angular error followed by pulse off time.
- Pulse on time and pulse off time were found to be insignificant parameters effecting the angular error but it was evident that the interaction of taper angle and pulse on time was effecting the angular error.
- Pulse off time was found to be the most significant parameter effecting surface roughness followed by pulse on time and it was evident that the interaction of taper angle and pulse off time was affecting the surface roughness.

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