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Effect of Process Parameters on Angular Error in Wire-EDM Taper Cutting of AISI D2 Tool Steel

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Abstract: *WEDM Taper-cutting is a very unique machining process which can generate curved surfaces on work pieces and it is especially important in the manufacturing of tools that require draft angles. One of the most important application of wire electrical discharge machining (WEDM) process used in production of precise complex geometries with inclined surfaces in hard material parts that are extremely difficult to machine by conventional machining process. The objective of the present work is to find the effect of process parameters such as taper angle, pulse on time and pulse off time on response variables such as angular error and cutting speed 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. Regression models are developed to relate the responses with process parameters. Analysis of variance (ANOVA) is conducted to study the contribution of each parameter affecting the responses. Results show that taper angle is the most significant parameter affecting angular error and pulse on time is the most significant parameter affecting cutting speed.*

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

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I. Introduction

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 Fig. 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.

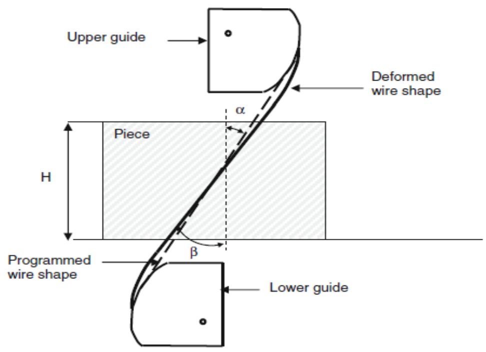

Figure.1: Theoretical and actual location of the deformed wire [9]

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 [3]. An attempt to study the in-process static mechanical behaviour of the wire had been carried out by Dauw and Beltrami [4]. 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 [5]. Sanchez et al. [6] 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. [7]. Puri and Bhattacharyya [8] 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.

An approach for predicting the angular error in wire-EDM taper cutting on AISI D2 tool steel was presented by Sanchez et al. [9]. Two original models for the prediction of angular error in WEDM taper-cutting process are presented by Plaza et al. [10]. Nayak & Mahapatra [11] adopted Multi response optimization approach to determine the optimal process parameters in WEDM taper cutting process. Yan and Huang [12] presented a closed-loop wire tension control system for a wire-EDM machine to improve the machining accuracy. Beltrami et al. [13] presented a wire deflection analysis showing that the wire deflection in wire EDM can be described as a bending string, featuring a parabolic deflection. Dynamic models of the feed control apparatus and wire tension control apparatus are analyzed and derived. 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 cutting speed (CS) in WEDM taper cutting on AISI D2 tool steel using design of experiments.

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.

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

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 Cutting speed 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. 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

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 parameters

Parameter	Symbol	Units	Value
Thickness	t	mm	40
Servo Voltage	(SV)	volts	10
Water Pressure	WP	Kg/cm^2	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	CS mm/min
	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	0.73
2	1	-1	-1	12	115	52	0.35	0.69
3	-1	1	-1	6	125	52	0.16	0.44
4	1	1	-1	12	125	52	0.42	0.49
5	-1	-1	1	6	115	58	0.22	0.48
6	1	-1	1	12	115	58	0.25	0.56
7	-1	1	1	6	125	58	0.03	0.45
8	1	1	1	12	125	58	0.41	0.51
9	-1.682	0	0	3.95	120	55	0.14	0.92
10	1.682	0	0	14.04	120	55	0.39	0.84
11	0	-1.682	0	9	112	55	0.31	0.50
12	0	1.682	0	9	128.4	55	0.33	0.52
13	0	0	-1.682	9	120	49.95	0.28	0.35
14	0	0	1.682	9	120	60.04	0.26	0.31
15	0	0	0	9	120	55	0.27	0.33
16	0	0	0	9	120	55	0.25	0.34
17	0	0	0	9	120	55	0.32	0.37
18	0	0	0	9	120	55	0.23	0.36
19	0	0	0	9	120	55	0.24	0.35
20	0	0	0	9	120	55	0.29	0.34

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 cutting speed (CS) 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

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

4.2. Cutting Speed

Based on lack of fit test, quadratic model is selected. After dropping insignificant terms, the reduced model of ANOVA for cutting speed is conducted. The model F-value of 39.71 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 A, B, C, BC, A^2 and B^2 are significant model terms. The final equation in terms of coded factors and actual values are given as

$$\frac{1}{CS} = -274.109 + 1.263 * A + 3.192 * B + 1.218 * B - 0.0098 * B * C - 0.070A^2 * C^2$$

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 Fig. 2 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).

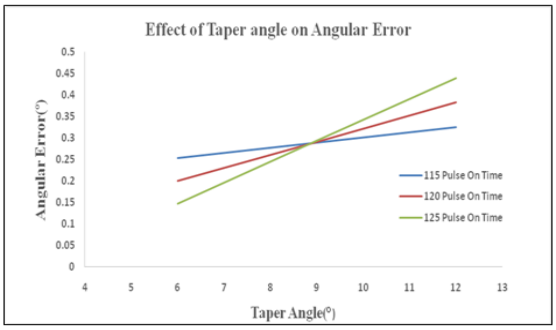

Figure 2: Effect of taper angle on angular error

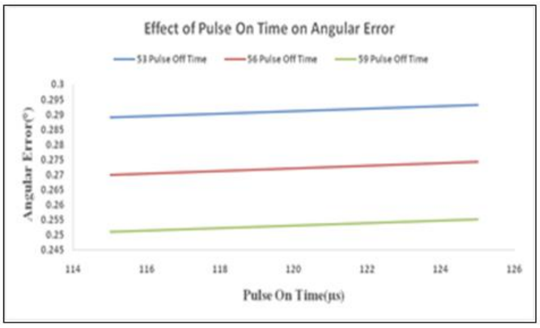

Figure 3: Effect of pulse on time on angular error

5.1.2. Effect of pulse on time on AE

From Fig. 3 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.

5.1.3. Effect of pulse off time on AE

Fig. 4 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 Cutting Speed (CS)

5.2.1. Effect of taper angle on CS

Subsequent Fig. 5 depicts the effect of taper angle on cutting speed 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 cutting speed up to an optimum value and increase then. It is observed that with respect to pulse on time for the increase in taper angle cutting speed 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 cutting speed with increase in taper angle and also since the wire has rigidity, a bending moment appears resulting in wire curvature before achieving the straight zone. A research has to be done on wire micro level for fruitful solution.

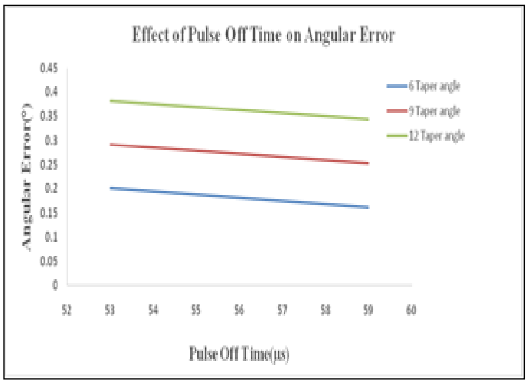

Figure 4: Effect of pulse off time on angular error

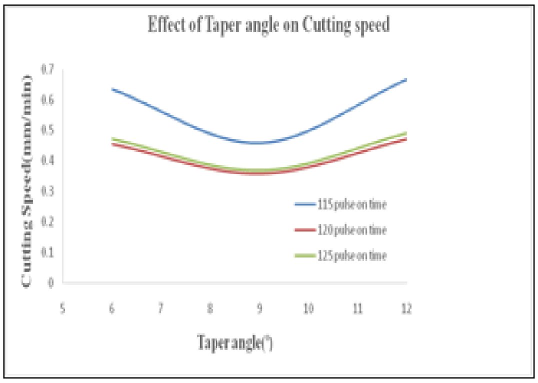

Figure 5: Effect of taper Angle on cutting speed

5.2.2. Effect of pulse on time on CS

From Fig. 6 , it can be seen that the higher the part thickness is, higher the deviation from the nominal angle is obtained for the parts with servo voltage 3V & 10V and a gradual increase in deviation was seen in piece with 20V, where as angular error decreased drastically for the parts with 30V & 37V servo voltage.

The contact length between wire and work piece increases with increase in thickness and decreases the cutting speed. Also for work pieces with higher values for servo voltage (30V & 37V), the gap between the work piece and the wire (electrode) becomes wider, which leads to decrease in the number of electric sparks resulting in rapid decrease in angular error. For work pieces with moderate value for servo voltage (20V) a gradual increase in deviation is observed and for lower values of servo voltage 3V & 10V increase in angular error is observed because of increase in the number of electric sparks.

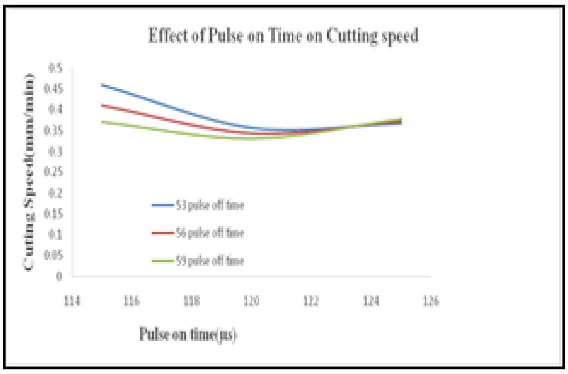

Figure 6: Effect of pulse on time on cutting speed

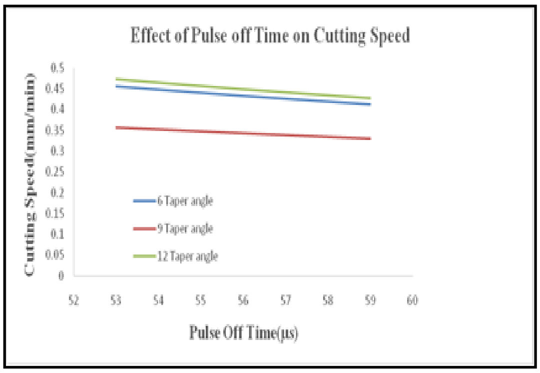

Figure 7: Effect of pulse off time on cutting speed

5.2.3. Effect of pulse off time on CS

Fig. 7 shows the effect of pulse off time on cutting speed with respect to different taper angles. It is observed that as the pulse off time increase the cutting speed decreased gradually. The increase in pulse off time provides better flushing off debris take place from the inter electrode gap resulting in decrease in cutting speed, a consequence of diminish in erosion from the work piece.

VI. 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 cutting speed 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 on time was found to be the most significant parameter effecting cutting speed followed by pulse off time and it as evident that the taper angle was the least significant parameter effecting cutting speed.

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