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Optimization of Process Parameters in Wire EDM Taper Cutting Process

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Abstract *- Wire EDM taper cutting process is used to achieve curved surfaces for dies and moulds which is difficult by traditional machining and straight cutting. The present research deals with the parametric optimization of taper cutting process using wire EDM on AISI D2 steel. Taper angle, servo voltage and part thickness are the process parameters considered in this study along with angular error, cutting speed and surface roughness as responses. Response surface methodology with central composite design was employed to design the experiments. Relation between input parameters and responses is determined by developing regression mathematical models and analysis of variance is implemented to test the competence of the above analysis. Optimal combination of process parameters for minimum angular error and surface roughness with maximum cutting speed were identified by using desirability approach. Results show that the optimal set of process parameters are taper angle 6°, part thickness 30 mm and servo voltage 22 V respectively achieving desirability value of 0.749 with response values as angular error 0.078°, cutting speed 0.423 mm/min and surface roughness 1.511 µm.*

Keywords — *Surface Finish, Wire EDM, Taper Angle, Cutting Speed, Angular Error, Response Surface Methodology, Analysis of Variance.*

I. INTRODUCTION

Wire electrical discharge machining (WEDM) is a broadly acknowledged non-traditional machining process for manufacturing parts with high hardness and complex shapes Achieving curved surfaces used for dies & moulds in WEDM process is difficult by traditional machining and straight cutting but it is possible to generate curved surfaces using WEDM's tapering ability [1]. In straight cutting, wire is straight and in taper cutting the upper and lower guides are moved apart to achieve required taper angle as shown in Fig. 1. Taper cutting process was first projected by Kinoshita et al. [2] by developing a linear model. Puri and Bhattacharyya [3] studied about wire lag phenomenon which results in Geometrical inaccuracy in wire electrical discharge machining. Kinoshita [4] have recommended a numerical control tool for wire discharge machining equipped with a taper machining correction feature for accurate taper machining. Dauw et al. [7] have carried out research work dealing with the effect of the forces effecting on the wire during the cutting process.

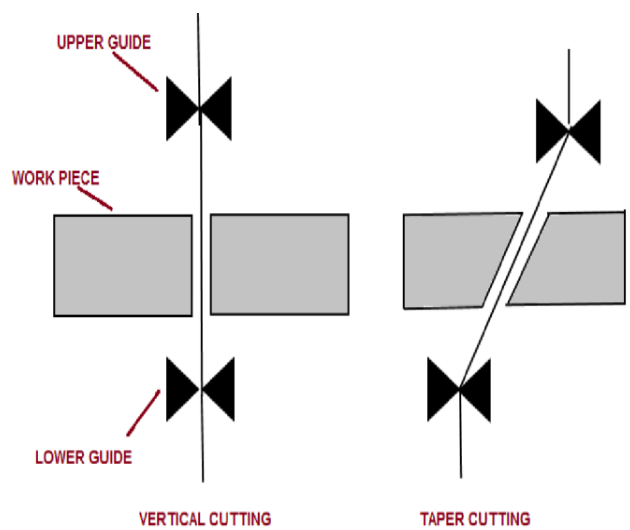

Fig. 1 Wire EDM Vertical and Taper cutting [12]

Hsue and Su [1] have developed a theoretical model meant for material removal analysis and Plaza et al. [6] have developed two models to predict the angular error in taper cutting using WEDM. Sanchez et al. [7] have introduced an approach to forecast the angular error in taper cutting using wire EDM and studied mechanical behaviour of wire using finite element simulation. In taper cutting axial force applied on the wire by machine was adjusted online by Chiu et al. [8] Nayak & Mahapatra [9] have employed Taguchi's design of experiment for investigating the effect of different input parameters on angular error, surface roughness and cutting speed in wire EDM process during taper cutting operation on austenitic stainless steel 304. Anshuman Kumar et al. [10] have developed mathematical models using nonlinear regression analysis for evaluating the influence of process parameters during taper cutting on inconel.

Literature shows that substantial quantity of work has been carried on straight cutting compared to taper cutting in WEDM. Present work is focused to study the effect of parameters such as taper angle, servo voltage and part thickness on responses as angular error (AE) and cutting speed (CS) in taper cutting with WEDM using response surface methodology. Also multi response optimization is carried using desirability function.

II. EXPERIMENTATION

Electronica Sprintcut WEDM with 0.25 mm diameter brass wire was used for experimentation. Deionised water was a source of dielectric medium during machining. Work material used is AISI D2 tool steel whose composition is presented in Table I. Square shaped work pieces of 20 numbers with various thickness (t) ie. 23mm, 30mm, 40mm, 50mm and 57mm and 10mm width (w) respectively were prepared by cutting and then grinding is performed to obtain better surface finish.

Table I. Chemical Composition of AISI D2 Steel

Consti-tuent	C	Si	Mn	S	P	Cr	Mo	Ni	Fe
% Composi-tion	1.60	0.72	0.51	0.025	0.041	12.05	0.61	0.35	balance

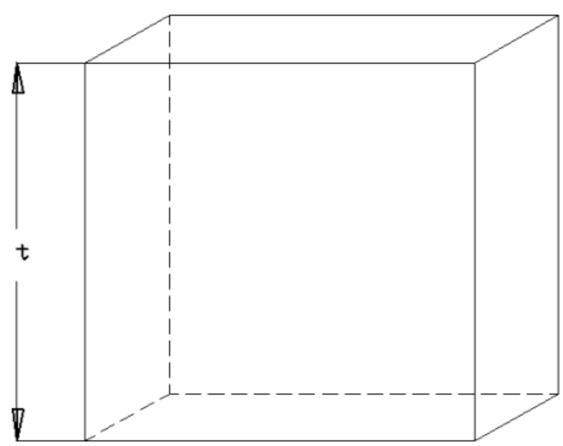

Fig. 2 Geometry of the work pieces before machining

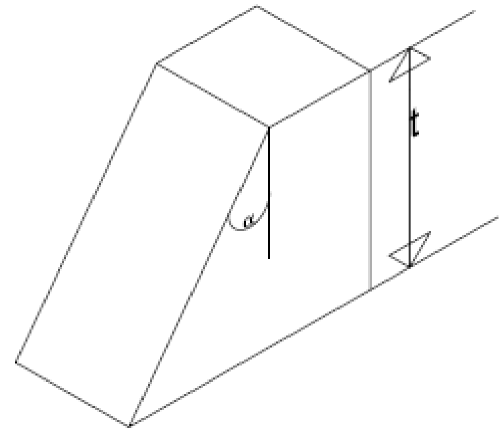

Fig. 3 Geometry of the work pieces after machining

Work pieces geometry before and after machining is shown in Fig. 2 and Fig. 3. The upper surface and lower surface of the work pieces act as a reference for measurement of the angle. Output responses are angular error (AE), surface roughness (SR) and cutting speed (CS). RSM based central composite design (CCD) is employed to design the experiments using design expert software. Mitutoyo SJ-301 surface roughness tester is used to measure surface roughness values and cutting speed is noted from display screen. Angular error which is the variation between the angle machined for and the angle obtained after taper cutting is measured using CNC coordinate measuring machine of Zeiss Prismo-5 model. Process parameters levels (coded and actual) are presented in Table II and constant parameters are shown in Table III. Experimental plan along with the summary of results are given in Table IV.

Table II: Levels of Process Parameters

Machining Parameters	Units	Levels				
		-1.682	**-1**	**0**	**+1**	**+1.682**
A - Taper Angle (TA)	(°)	4	6	9	12	14
B - Thickness (t)	mm	23	30	40	50	57
C - Servo Voltage (SV)	volts	3	10	20	30	37

Table III: Constant Process Parameters

Parameter	Symbol	Units	Value
Pulse on Time	Ton	µs	120
Pulse off Time	Toff	µs	56
Water Pressure	WP	kg/cm^2	10
Wire Tension	WT	gms	9
Wire Feed	WF	m/min	5
Peak Current	IP	Ampere	12
Servo Feed	SF	mm/min	2100

Table IV: Experimental Plan & Summary

Std. Order	Coded Factors			Actual Factors			Responses		
	A (°)	B (mm)	C (V)	Taper Angle (°)	Thickness (mm)	Servo Voltage (V)	Angular Error (°)	Cutting Speed (mm/min)	Surface Roughness (μm)
1	1.68	0	0	12	50	10	0.065	0.27	1.81
2	0	0	0	4	40	20	0.037	0.31	2.75
3	-1	-1	-1	9	57	20	0.018	0.22	2.38
4	0	0	0	9	40	20	0.037	0.30	3.35
5	1	1	-1	6	50	30	0.015	0.21	1.44
6	0	0	0	9	40	3	0.032	0.35	2.56
7	1	-1	1	9	40	20	0.128	0.32	1.92
8	0	0	0	12	30	10	0.031	0.47	1.80
9	-1.68	0	0	9	40	20	0.003	0.32	2.67
10	1	-1	-1	9	40	37	0.059	0.22	3.12
11	-1	-1	1	9	40	20	0.026	0.31	2.91
12	0	0	0	9	40	20	0.038	0.31	2.85
13	-1	1	-1	6	30	30	0.013	0.37	2.80
14	0	-1.68	0	9	40	20	0.089	0.31	2.25
15	1	1	1	12	50	30	0.055	0.20	2.23
16	0	0	0	6	30	10	0.038	0.48	2.26
17	0	0	1.68	4	40	20	0.075	0.32	2.03
18	-1	1	1	9	23	20	0.019	0.55	2.12
19	0	0	-1.68	12	30	30	0.006	0.35	2.46
20	0	1.68	0	6	50	10	0.022	0.27	2.07

III. RESPONSE SURFACE REGRESSION ANALYSIS

The influence of individual parameters and their interactions on responses is obtained by performing RSM analysis using design expert software. Sequential model sum of squares were calculated for individual responses to pick the highest order polynomial. Lack of fit test for each model is calculated and presented. For the selection of model, the lack-of-fit should be insignificant (smallest F value). The lack-of-fit is the deviation of the data about the model fitted. Initially all quadratic terms A, B, C, AB, AC, and BC were included in the model and after removing insignificant terms reduced model of ANNOVA are presented. Other ANOVA parameters are obtained to check that the model adequacy.

The final regression equations for individual responses in terms of coded values and actual values are obtained.

A. Angular Error (AE)

The reduced model of ANOVA for angular error conducted after dropping insignificant terms is shown in Table 4. The model F value of 9.06 indicates the model significane and the values of Prob>F less than 0.05 specify that the model terms are significant as A, C, AC and BC in this case.

The final regression equation for AE in terms of actual values is given as

$$\begin{aligned}\text{Ln(Angular Error)} = &-4.8609 - 0.3176\times\text{Taper Angle} + 0.1601\times\text{Thickness}\\ &+0.0452\times\text{Servo Voltage} + 0.0247\times\text{Taper Angle}\times\text{Servo Voltage}\\ &-0.0073\times\text{Thickness}\times\text{Servo Voltage}\end{aligned} \quad ..(1)$$

Table IV. ANOVA for Angular Error

Source	Sum of Squares	DOF	Mean Square	F-value	p-value (Prob>F)	Remarks	% Contribution
Model	13.68083	5	2.736166	9.059684	0.0005	Significant	
A-Taper Angle	3.849923	1	3.849923	12.74743	0.0031		28.13
B-Part Thickness	0.249794	1	0.249794	0.827091	0.3785		1.82
C-S Voltage	1.1505	1	0.878269	3.8110	0.00092		8.41

Source	Sum of Squares	DOF	Mean Square	F-value	p-value (Prob>F)	Remarks	% Contribution
AC	4.403924	1	4.403924	14.58178	0.0019		32.18
BC	3.8867	1	4.298919	12.8742	0.0021		28.41
Residual	4.228218	14	0.302016				
Lack of Fit	3.602606	9	0.40029	3.199184	0.1067	Not Significant	
Pure Error	0.625612	5	0.125122				
Corrected Total	17.90905	19					

Results obtained from ANOVA for AE show that taper angle with 28.13% contribution is the most significant parameter influencing AE followed by servo voltage with 8.41%. It was also observed that an interaction of servo voltage along with taper angle and part thickness had a high influence on AE.

B. Cutting Speed (CS)

ANOVA for cutting speed is conducted and presented in Table 5. The model F value of 807.08 show the model is important and the values of Prob> F less than 0.05 specify that the model terms are significant as A, B, C, B2, C2 in this case. The final regression equation for CS in terms of actual values is given as

$$\begin{aligned}\text{Ln(CS)} = {} & 0.6499 + 0.0025 \times \text{Taper Angle} - 0.0584 \times \text{Thickness} + 0.0059 \\ & \times \text{Servo Voltage} - 0.0003 \times \text{Taper Angle} \times \text{Servo Voltage} + 0.0003 \\ & \times \text{Thickness}^2 - 0.0004 \times \text{Servo Voltage}^2\end{aligned} \quad \ldots..(2)$$

Table V. ANOVA for Cutting Speed

Source	Sum of Squares	DOF	Mean Square	F-value	p-value (Prob>F)	Remarks	% Contribution
Model	1.3706	6	0.2284	807.0772	< 0.0001	Significant	
A- Taper Angle	0.0023	1	0.0023	8.270879	0.0130		0.14
B- Part Thickness	0.9856	1	1.0555	3728.971	< 0.0001		71.91
C-Servo Voltage	0.2908	1	0.2608	1099.5811	< 0.0001		21.21
AC	0.0008	1	0.0008	3.064761	0.1036		0.05
B^2	0.0214	1	0.0214	75.70562	< 0.0001		1.53
C^2	0.0251	1	0.0251	88.68632	< 0.0001		1.82
Residual	0.0036	13	0.0002				
Lack of Fit	0.0007	8	.00009	0.158862	0.9883	Not Significant	
Pure Error	0.0029	5	0.0005				
Corrected Total	1.3743	19					

ANOVA results of CS indicate that part thickness is most significant parameter effecting CS with 71.91% contribution and next servo voltage with 21.21%.

C. Surface Roughness (SR)

ANOVA result in terms of surface roughness is presented in Table VI. The Model F value of 55.55 indicates the model is important and the values of Prob> F less than 0.05 indicate that the model terms are significant as A, B, C, B2, C2 in this case.

The final regression equation for SR in terms of actual values is given as

$$\begin{aligned}\text{SR} = {} & 2.3806 + 0.1713 \times \text{Taper Angle} - 0.069861 \times \text{Thickness} - 0.0591 \times \text{Servo Voltage} + 1.15 \times 10^{-03} \\ & \times \text{Thickness}^2 + 1.04 \times 10^{-03} \times \text{Servo Voltage}^2\end{aligned} \quad \ldots..(3)$$

Table VI. Analysis of Variance for Surface Roughness

Source	Sum of Squares	DOF	Mean Square	F-value	p-value (Prob>F)	Remarks	% Contribution
Model	3.92	5	0.78	55.55	< 0.0001	Significant	
A- Taper Angle	2.46	1	2.76	195.61	< 0.0001		62.75
B- Part Thickness	0.65	1	0.65	46.18	< 0.0001		16.58
C-Servo Voltage	0.42	1	0.42	29.78	0.0001		10.71
B^2	0.18	1	0.18	12.83	0.0033		4.59
C^2	0.15	1	0.15	10.57	0.0063		3.82
Residual	0.18	13	0.014				
Lack of Fit	0.059	8	7.40x10-03	0.3	0.9373		
Pure Error	0.12	5	0.025			Not Significant	
Corrected Total	4.1	18					

From ANOVA related to SR it is clear that taper angle with 62.75% contribution is highly influencing SR followed by part thickness with 16.58% and servo voltage with 10.71% contribution.

IV. MULTI OBJECTIVE OPTIMIZATION

The multi-response optimization was carried out using desirability function [11] using design expert software which involves calculating (Ri) the response values of using the final regression equation for each. Each Ri is then transformed to the corresponding desirability value (di) using Eq. (4). Then all the three di values are gathered into a desirability of the level of parameters (D) using Eq. (5).

di= (Ri-Rmin/Rmax-Rmin)r …(4)

Where di: value of the desirability of the individual responses Ri, r: represents how important is to hit the target value and =1, Rmin is the minimum and Rmax is the maximum values of AE, CS and SR of the whole experiments.

$$D = (d1\times, d2\times, \ldots\times dk)^{1/k} \quad \ldots(5)$$

Where k is the responses number.

The highest value of D is obtained by searching all parameter with condition of minimum angular error, maximum cutting speed and minimum surface roughness, and suggesting optimal set of input parameters to achieve the research goals. Table 6.15 shows process parameter combinations of 18 levels which will provide maximum value of composite desirability. The optimized parameters levels of the machining are obtained respectively achieving desirability value of 0.749.

Table VII. Optimal Solutions for Angular Error, Cutting Speed and Surface Roughness

No.	Parameter Levels			Response Values			Desirability	
	Taper Angle (°)	Thickness (mm)	Servo Voltage (V)	Cutting Speed (mm/ min)	Angular Error (°)	Surface Roughness (µm)		
1	6	30	22.19	0.423523	0.078457	1.51117	0.749	Selected
2	6	30	22.11	0.423981	0.07861	1.51207	0.749	
3	6	30	21.83	0.425722	0.079198	1.51566	0.749	
4	6	30.01	22.32	0.422469	0.078179	1.5095	0.749	
5	6	30.01	21.66	0.426554	0.079562	1.51788	0.749	
6	6.01	30	21.95	0.424982	0.07909	1.51548	0.749	
7	6	30	23.32	0.416328	0.076154	1.49901	0.749	
8	6	30	23.97	0.412117	0.074881	1.49355	0.748	
9	6	30.15	22.32	0.420454	0.078153	1.5089	0.748	
10	6	30	19.78	0.437653	0.083574	1.54751	0.747	
11	6	30	19.4	0.439758	0.084422	1.55464	0.746	
12	6.1	30	21.19	0.429229	0.082294	1.5426	0.744	
13	6.13	30	22.66	0.420048	0.080041	1.52892	0.742	
14	6.1	30	24.74	0.406527	0.07559	1.50588	0.741	
15	6	31.67	21.15	0.405236	0.081317	1.52039	0.729	
16	6	30	11.86	0.471417	0.102887	1.76842	0.711	
17	6.43	30	10.59	0.47387	0.103841	1.89395	0.691	

No.	Parameter Levels			Response Values			Desirability	
	Taper Angle (°)	Thickness (mm)	Servo Voltage (V)	Cutting Speed (mm/ min)	Angular Error (°)	Surface Roughness (µm)		
18	6	30.42	10	0.469103	0.112012	1.84101	0.687	

V. CONCLUSIONS

Based on RSM analysis and multi response optimization using desirability approach the following conclusions are drawn from the results obtained.

Regression equations are successfully used to develop the model for angular error, cutting speed and surface roughness.

Taper angle with 28.13% contribution was the most important parameter influencing AE followed by servo voltage with 8.41%. It was also observed that an interaction of servo voltage along with taper angle and part thickness had a high influence on AE.

Part thickness was found to be the most influencing parameter effecting CS with 71.91% contribution and next servo voltage with 21.21%.

Taper angle with 62.75% contribution was highly influencing SR followed by part thickness with 16.58% and servo voltage with 10.71% contribution.

The optimal set of process parameters obtained are taper angle 6°, part thickness 30 mm and servo voltage 22.19 V respectively achieving desirability value of 0.749 with response values as angular error 0.784° , cutting speed 0.423 mm/min and surface roughness 1.511 µm.

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