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Study on Effect of process parameters on angular error and Cutting speed in wire-EDM taper cutting

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Abstract: Electrical discharge machining (EDM) is a well-established machining option for manufacturing geometrically complex or hard material parts that are extremely difficult-to-machine by conventional machining processes. WEDM Taper cutting involves the generation of inclined surfaces and possesses significant bearing in manufacturing of tooling requiring taper or draft angles. The objective of the present work is to find the effect of process parameters such as taper angle, wire feed and wire tension on response variables such as angular error, cutting speed and surface roughness by WEDM taper cutting. Machining was carried on AISI D2 tool steel and experiments were planned using Response Surface Methodology (RSM) – Central Composite design (CCD) involving three variables with five levels. Regression models relating the responses to the process parameters are developed and separate analysis of variance (ANOVA) is used to analyze and calculate 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: ***Taper Cutting, wire feed, wire tension, Angular Error, Response Surface Methodology***

I. INTRODUCTION

Wire-electro discharge machining (WEDM) has become an important non-traditional machining process, as it provides an effective solution for producing components made of difficult-to-machine materials like titanium, zirconium, etc., and intricate shapes, which are not possible by conventional machining methods [2]. Taper cutting is one of the most important application of wire electrical discharge machining (WEDM) process involves in the generation of inclined ruled surfaces which is important in the manufacturing of tooling requiring draft angles [1]. In wire-EDM the taper angle is achieved by applying a relative movement between the upper and lower guides during which the wire is subjected to deformation resulting deviations in the inclination angle of machined parts.

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. The main factors contributing to the geometrical inaccuracy of the WEDMed part are the various process forces acting on the wire causing it to depart for the programmed path [11].

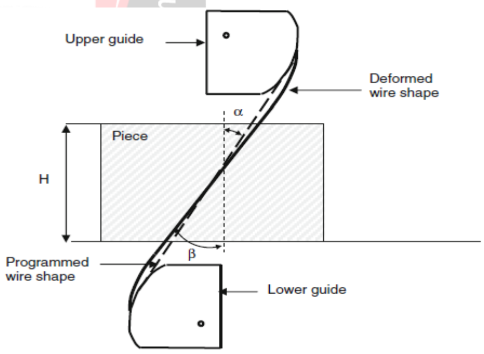

Figure.1: Theoretical and actual location of the deformed wire [12]

II. LITERATURE REVIEW

The term taper-cutting is one of the most important applications of WEDM process commonly used for WEDM operations aiming at generating parts with tapered profiles. Kinoshita et al. [3] was the first to propose the problem of taper cutting and developed a linear model for wire deformation without considering the forces acting during the process. Vikram Singh and S.K. Pradhan [4] investigated the effects of various WEDM process parameters such as pulse on time, pulse off time, servo voltage and wire feed rate and obtained the optimal settings of machining parameters at which the Material Removal

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Rate (MRR) and cutting rate are maximum and the Surface Roughness (SR) is minimum in a range. Brajesh Kumar Lodhia and Sanjay Agarwal [5] made an attempt to optimize the machining conditions for surface roughness based on (L9 Orthogonal Array) Taguchi methodology. The optimal machining parameters for the maximum cutting speed and minimum surface roughness using Taguchi methodology were found by Selvakumar et al. [6]. Pragya Shandilya et al. [7] have focussed to optimize the process parameters during machining of SiCp / 6061 Al metal matrix composite (MMC) using response surface methodology (RSM). Sanchez et al. [1] have used new approach to the prediction of angular error in wire-EDM taper-cutting. Nayak & Mahapatra [8] adopted Multi response optimization approach to determine the optimal process parameters in WEDM taper cutting process. Sanchez et al. [9] presented computer simulation software for the analysis of error in wire EDM taper-cutting. Rao and Pawar [10] developed mathematical models using response surface modelling (RSM) for correlating the inter-relationships of various WEDM parameters.

Literature review reveals that less attention has been focused on taper cutting in WEDM. Researchers have worked more on straight cutting and WEDM taper cutting operations is still leftover as an important issue. Hence the present work is focused on investigating the effect of various process parameters such as taper angle, wire feed and wire tension 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.

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 1: Chemical Composition of AISI D2 Tool Steel

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 (CS) 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 summary of results are given in Table 4. Two level full factorial design with 6 central runs and 6 axial runs leading to central omposite 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	°	3.95	6	9	12	14
Wire feed	mm/min	2.318	4	5	6	8
Wire tension	g	7.31	8	9	10	10.68

Table 3: Controllable process parameters

Parameter	Symbol	Units	Value
Servo voltage	SV	volts	10
Part thickness	t	mm	40
Water Pressure	WP	Kg/cm2	10
Pulse on Time	Ton	µs	120
Pulse off Time	Toff	µs	55

Table 4: Experimental plan & summary of results

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Std	Run	Coded values			Actual values			AE degrees	CS mm/min
		Taper angle (degrees)	Wire feed mm/min	Wire tension(g)	Taper angle (degrees)	Wire feed mm/min	Wire tension(g)		
1	19	-1	-1	-1	6	4	7	**0.092**	1.105
2	6	1	-1	-1	12	4	7	0.555	0.986
3	13	-1	1	-1	6	6	7	0.220	0.914
4	7	1	1	-1	12	6	7	0.544	0.812
5	15	-1	-1	1	6	4	9	0.094	0.927
6	20	1	-1	1	12	4	9	0.676	1.026
7	3	-1	1	1	6	6	9	0.275	0.983
8	1	1	1	1	12	6	9	0.533	1.012
9	18	-1.682	0	0	4	5	8	0.210	1.054
10	16	1.682	0	0	14	5	8	0.572	0.889
11	12	0	-1.682	0	9	3	8	0.128	0.924
12	5	0	1.682	0	9	7	8	0.376	0.791
13	10	0	0	-1.682	9	5	6	0.589	0.912
14	2	0	0	1.682	9	5	10	0.58	1.043
15	8	0	0	0	9	5	8	0.129	0.994
16	17	0	0	0	9	5	8	0.190	0.987
17	11	0	0	0	9	5	8	0.115	**1.112**
18	14	0	0	0	9	5	8	0.112	1.023
19	9	0	0	0	9	5	8	0.110	0.951
20	4	0	0	0	9	5	8	0.300	1.74

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 as shown in Table 5.

The Model F-value of 25.53 implies 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, AB, and C^2** are significant model terms.

The final equation in terms of actual values are given as:

$$Angular\ Error = 9.094+0.176\times T.angle-0.138\times W.feed-2.456\times W.tension-0.021\times T.angle\times W.feed+0.036\times W.feed^2 + 0.15\times W.tension^2$$

Table 5: Analysis of Variance (ANOVA) for Angular Error

Source	Sum of Squares	df	Mean Square	F	p-value Prob > F	Remark
Model	0.711	6.000	0.119	**25.534**	< 0.0001	**significant**
A-T angle	0.421	1.000	0.421	**90.615**	**< 0.0001**	
B-W feed	0.018	1.000	0.018	3.962	0.0720	
C-W tension	0.001	1.000	0.001	0.179	0.6800	
AB	0.026	1.000	0.026	5.525	**0.0384**	
B^2	0.018	1.000	0.018	3.849	0.0756	
C^2	0.319	1.000	0.319	68.696	**< 0.0001**	

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Residual	0.051	11.000	0.005			
Lack of Fit	0.023	6.000	0.004	**0.671**	0.6816	**not significant**
Pure Error	0.028	5.000	0.006			
Cor Total	0.763	17.000				

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 and shown in Table 6.

The Model F-value of 10.43 implies the model is significant. There is only a 0.02% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B, C, AC, BC, B^2 are significant model terms.

The final equation in terms of coded factors and actual values are given as:

$$Cutting\ Speed=3.127-0.127-0.019-0.367\times W.tension+0.014\times T.angle\times W.tension+0.051\times W.feed\times W.tension-0.043\times W.feed^2$$

Table 6: Analysis of Variance (ANOVA) for Cutting Speed

Source	Sum of Squares	df	Mean Square	F	p-value Prob > F	Remark
Model	0.10514	6	0.017523	10.43328	0.0002	**significant**
A-T angle	0.010624	1	0.010624	6.325401	0.0258	
B-W feed	0.020851	1	0.020851	**12.41483**	0.0037	
C-W tension	0.008646	1	0.008646	5.148078	0.0409	
AC	0.015753	1	0.015753	9.379348	0.0091	
BC	0.021528	1	0.021528	12.81776	0.0034	
B^2	0.027737	1	0.027737	16.51425	0.0013	
Residual	0.021834	13	0.00168			
Lack of Fit	0.013501	8	0.001688	1.012566	0.5193	not significant
Pure Error	0.008333	5	0.001667			
Cor Total	0.126974	19				

V. RESULTS AND DISCUSSION

Based on response surface model after regression analysis, the results in terms of effect of taper angle, wire feed and wire tension 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

Figure. 2 shows the effect of taper angle on angular error at different wire feed values (4, 5 & 6 mm/min), and at constant wire tension value of 9 mm/min respectively. Taper angle is the most effecting among the other parameters on angular error with F-value 90.61 according to ANOVA shown in Table 5.22 above. The graphs show that the angular error increased with increase in taper angle. At higher value of taper angle, the wire vibrations are more, leading to more angular error. The maximum increase in angular error was 0.96° for graph with wire feed 5 mm/min.

5.1.2. Effect of wire feed *on AE*

Figure. 3 shows the effect of wire feed on the angular error for various wire tension values (8, 9 & 10 g) at constant taper angle of 9° respectively. It is evident that with increase in wire feed the angular error initially decreased till optimum value and then increased gradually. At low amount of feed, the material removal rate is more due to the high energy of the wire leading to lower angular error compared to higher amount of feed.

5.1.3. Effect of wire tension *on AE*

Figure. 4 shows the effect of wire tension on angular error at different taper angles at constant wire feed of 5mm/min respectively. With increase in wire tension the angular error initially decreased till optimum value of wire tension 8 g and then increased sharply. If wire tension is moderate vibrations are also moderate, leading to reduce angular error. At higher wire tension vibrations are less and should decrease the angular error but, taper angle is the most significant parameter effecting so, instead, it causes more angular error at higher wire tension values.

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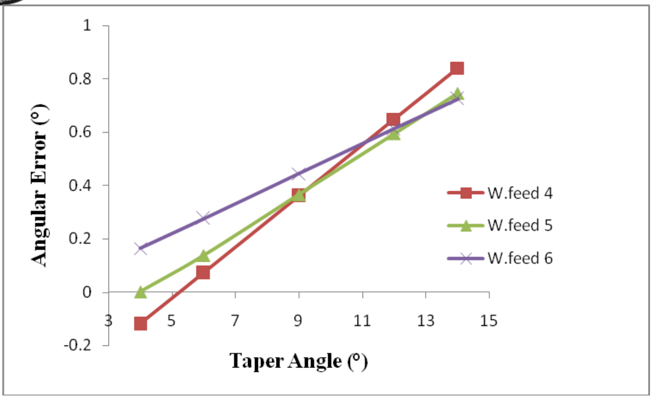

Figure 2: Effect of taper angle on angular error

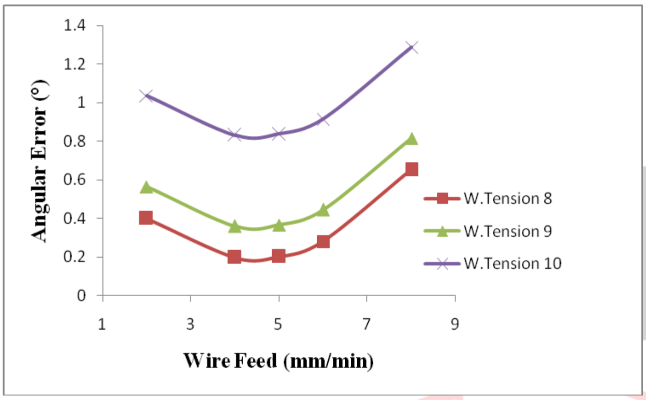

Figure 3: Effect of wire feed on angular error

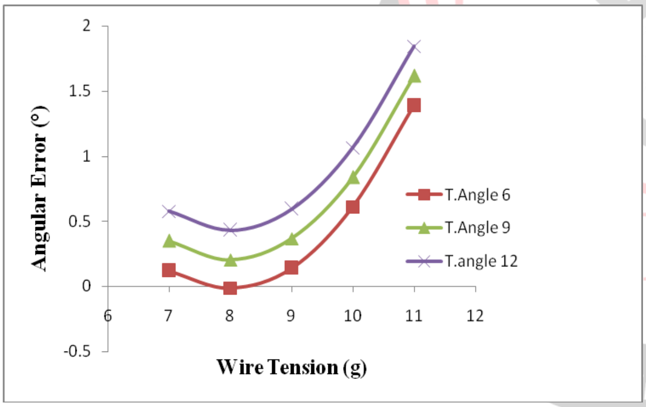

Figure 4: Effect of wire tension on angular error

5.2 Cutting Speed (CS)

5.2.1. Effect of taper angle on CS

Figure. 5 demonstrates the relationship between taper angle and cutting speed for various wire feeds at constant wire tension of 9 g. Increase in taper angle increases the displacement between the guides and the contact length between the wire and guides also increases resulting in increase in the influence of the axial force acting on the wire in the cutting zone which gradually decreases the cutting speed but the influence of wire feed leads to a small increase in the cutting speed gradually.

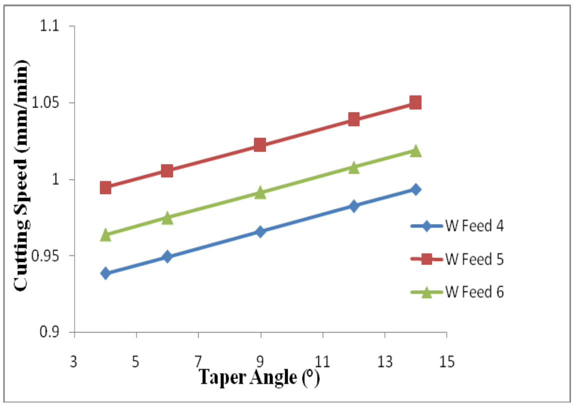

Figure 5: Effect of taper angle on cutting speed

5.2.2. Effect of wire feed *on CS*

According to ANOVA test wire feed is found to be the most effecting parameter on angular error with F-value 12.41. Figure. 6 shows the effect of wire feed on cutting speed for different wire tensions at constant taper angle 9° respectively. Cutting speed increased rapidly due to increase in wire feed and decreased gradually. Higher wire feed, leads to lower the heat generated to melt the metal per unit time, causing less speed required for cutting.

5.2.3. Effect of wire tension on CS

Figure. 7 shows the effect of wire tension on cutting speed for different taper angles and at constant wire feed **5 mm/min** respectively. Wire tension has less significant on the cutting speed, but due to the influence of taper angle cutting speed decreases for lower taper angles (6°) and increases for higher taper angles (9° & 12°). At higher wire tension vibrations are less and should decrease the cutting speed but, increase in taper angle leads to increase in cutting speed.

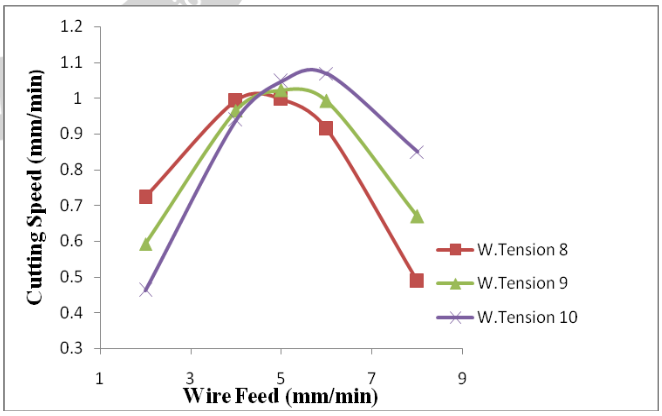

Figure 6: Effect of wire feed on cutting speed

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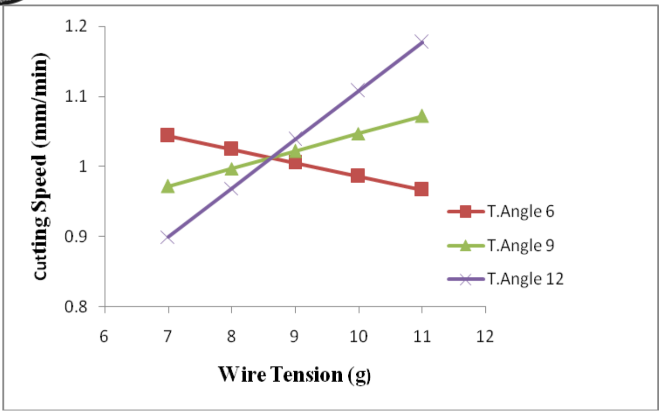

Figure 7: Effect of wire tension on cutting speed

VI. CONCLUSIONS

Based on response surface model after regression analysis, the results in terms of effect of taper angle, wire feed and wire tension on angular error and cutting speed are concluded as.

- Taper angle is found to be the most significant parameter effecting angular error and it is evident that the wire feed and wire tension are insignificant parameters effecting AE.
- An interaction effect of taper angle influencing CS along with wire tension was observed.
- Minimum angular error of 0.092° is recorded at TA 6°, WF 4 mm/min & WT 7g respectively
- Wire feed was found to be the most significant parameters effecting cutting speed followed by taper angle and it is evident that the wire tension is insignificant parameters effecting CS.
- An interaction effect of wire feed influencing CS along with wire tension was observed.
- Maximum cutting speed of 1.07 mm/min was obtained at TA 9°, WF 5 mm/min & WT 8g respectively.

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