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Research paper



Multi-objective optimization of WEDM process parameters for taper cutting of AISI D2 tool steel

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Abstract

Wire electrical discharge machining (WEDM) process is one of the most popular method for the producing complex geometries in hard and wear resistant materials such as those used in tooling industry. This taper cutting involves in making of inclined surface, and it is particularly significant in the manufacturing of tooling that requires draft angles. In the present paper, experiments were conducted in order to find the effect of process parame- ters such as taper angle, geometrical thickness and servo voltage on response variables such as angular error and cutting speed on AISI D2 tool steel using statistical design of experiments. The experiments were planned using Central Composite design (CCD) which is part of Response Surface Methodology (RSM) – involving three variables with five levels. Multi objective optimization was conducted for maximizing the Cutting speed and minimizing the angular error using genetic algorithm. The optimization procedure leads to creation of non-dominated optimal points which gave an insight regarding the optimal operating conditions of the process.

Keywords: *Wire EDM; Taper Cutting; Cutting Speed; Angular Error; Response Surface Methodology; Genetic Algorithm.*

1. Introduction

Wire electrical discharge machining (WEDM) has been found to be an extremely potential electro-thermal process in the field of conduc- tive material machining which is employed for the parts demanding higher accuracy levels with varying hardness or complex shapes. Ta- per cutting is one of the most important applications of WEDM pro- cess that involves the generation of inclined surfaces and possesses significant bearing in manufacturing of tooling requiring taper or draft angles. The taper angle is achieved by applying a relative dis- placement between the upper and lower guides of the wire as shown in Fig. 1. The maximum angle that can be cut depends upon part thickness, but values about 30° can be easily achieved [2].

The main factors contributing to the geometrical inaccuracy of the WEDMed part are the various process forces acting on the wire caus- ing it to depart for the programmed path [3]. The problem of taper cutting was first time proposed by Kinoshita et al. [4] who developed a linear model for wire deformation neglecting the forces produced during the process. Computer simulation software for the analysis of error in wire EDM taper-cutting was presented by Sanchez et al. [5]. Two models for the prediction of angular error in WEDM taper cut- ting ware developed by Plaza et al. (2009). Nayak & Mahapatra [6] adopted Multi response optimization approach to determine the op- timal process parameters in WEDM taper cutting process.

Since the wire is subjected to deformation in wire EDM taper cutting process, deviations are obtained in the inclination angle of machined parts. As a result, the machined part losses its precision. Hence, se- lection of the process parameters is a major issue in the field of taper cutting operation in WEDM. However, the traditional Taguchi meth- od cannot solve the multi-objective optimization problem. To over- come this limitation genetic algorithm is applied to simultaneously optimize the process parameters for minimizing angular error and maximizing cutting speed during taper cutting in WEDM.

The present work is focused on investigating the effect of various process parameters of WEDM such as taper angle, part thickness and servo volt- age (SV) on responses such as angular error (AE) and cutting speed (CS) in taper cutting of AISI D2 tool steel. Further, angular error (AE) and cutting speed (CS) were exposed to multiple objective optimization using genetic algorithm (GA) approach. RSM model aids in process under- standing while the Pareto optimal solutions generated from GA approach facilitates to identify optimal operating conditions.

2. Materials and method

Experiments were conducted on AISI D2 steel using Electronica Sprintcut WEDM and brass wire electrode of 0.25 mm diameter. Deionised water was used as a dielectric medium. The work pieces were prepared by cut- ting into the sizes as per the experimental plan as shown in Table 1 and 2 with 10mm width (w) and then grounded in order to get good finish. The lower and upper surfaces of the work parts are grounded, so that they can be used as a reference for measurement of the angle. Angular error (AE) and Cutting speed were studied 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 de- sign was used to conduct experiments. Coded and actual levels of process parameters are presented in

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Table 1 & the experimental plan and summary of results are given in Table 2.

Table 1: Coded and Actual Levels of Various Process Parameters

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

Table 2: Experimental Plan and Results Summary

S. No	Coded factors			Actual factors				
	Taper angle A (°)	Thick- ness B (mm)	Servo Volt- age C (Volt)	Taper angle (°)	Thick- ness (mm)	Servo volt- age (Volt)	CS mm/ min	AEde- gree s
1	1.68	0	0	14.7	20	40	0.48	0.155
2	0	0	0	8	20	40	0.47	0.037
3	-1	-1	-1	4	10	20	0.27	0.605
4	0	0	0	8	20	40	0.27	0.406
5	1	1	-1	12	30	20	0.37	0.057
6	0	0	0	8	20	40	0.35	0.430
7	1	-1	1	12	10	60	0.21	0.018
8	0	0	0	8	20	40	0.2	0.015
9	-1.68	0	0	1.27	20	40	0.32	0.031
10	1	-1	-1	12	10	20	0.31	0.588
11	-1	-1	1	4	10	60	0.55	0.332
12	0	0	0	8	20	40	0.22	0.385
13	-1	1	-1	4	30	20	0.35	0.143
14	0	-1.68	0	8	3.18	40	0.22	0.108
15	1	1	1	12	30	60	0.32	0.157
16	0	0	0	8	20	40	0.3	0.134
17	0	0	1.68	8	20	73.63	0.31	0.236
18	-1	1	1	4	30	60	0.31	0.270
19	0	0	-1.68	8	20	6.364	0.31	0.117
20	0	1.68	0	8	36.8	40	0.32	0.248

3. RSM analysis

Response surface regression analysis is done to evaluate the effect of indi- vidual parameter and their interactions on response parameters viz. cutting speed (CS) and angular error (AE) using Stat-Ease Design Expert software. Separate Analysis of Variance (ANOVA) was conducted for cutting speed and angular error respectively.

Based on lack of fit test, quadratic model is selected for cutting speed. After dropping insignificant terms, the reduced model of ANOVA for cutting speed is shown in Table 3.The model F-value of 807.077 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 0.1 indicates model terms are significant. In this case A, B, C, AC, B^2 and C^2 are significant model terms. Similar procedure was adopted for angular error also. Depending on coefficients calculated, the final regression equa- tions in terms of actual values for cutting speed and angular error was presented below.

The final equation for Cutting speed in terms of actual values:

$$\text{Ln (Cutting speed)} = 0.650+0.0026*A+0.06*B+0.006*C-0.0003*A*C+0.0004*B^2 -0.0004*C^2$$

$$\text{Ln (Angular Error)} = 4.861+0.318*A+0.16*B+0.452*C+0.025*A*C- 0.0073*B*C$$

4. Optimization study

Simultaneous optimization of cutting speed and error falls in the ambit of multi-objective optimization. There is no unique solution to a multi objective optimization problem, but a set of mathematically equally good solutions known as non-dominated or Pareto optimal solutions can be produced. Pareto front catch- es the trade-offs between conflicting objectives and detects those solutions which are normally non-dominated. It consists of those members of the population for which there exists no solu- tion which is better in criteria than the Pareto set member. The ability to characterize Pareto front allows to focus on the top solutions for inspection and trade-offs of contradictory variables. Pareto front representation can be used to scan quickly for sug- gesting solutions from large populations of expressions and focus subsequent analysis effort on those solutions.

The aim of this work is to find the optimal combination of input parameters with a maximum cutting speed and the minimum angular error. It has been found that when the cutting speed increases, error also increases. Because of the inconsistency of the performance measures, only a combination of input parame- ters does not serve the purpose. Consequently, a set of optimal solutions (i.e. Pareto optimally solution) instead of an optimal combination can be obtained. In the present study, the problem of optimization of wire EDM has been framed as a multi- objective optimization problem, since the determination of the optimum machining conditions includes a conflict among max- imizing the cutting speed and to minimizing angular error.

MATLAB optimization toolbox (R2013a) was used to create the Pareto front for cutting speed and angular error using 'gamultiobj' function. " gamultiobj " in optimization toolbox uses a set of operators that apply to the entire population set that is considered. The initial population is randomly generated by default. The next generation of the population is calculated to use the non-dominated rank and a crowding distance measurement of individuals in the current generation.

5. Results and discussion

Based on response surface model after regression analysis, the results in terms of effect of taper angle, part thickness & servo voltage on cutting speed and angular error are calculated and discussed in the following sections.

Cutting Speed (CS)

It is observed from the Fig.1 that with increase in taper angle the cutting speed is almost constant for work pieces of different thickness. Increase in taper angle increases the displacement between

the guides and the contact length between 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.

From the Fig.2 it is also depicted that the cutting speed decreases sharply with the increase in part thickness. As the thickness of work piece increases the area of contact between wire and work piece also increase which increases the machining time and de-creases the cutting speed.

Table 3: ANOVA for Cutting Speed after Dumping Insignificant Terms

Source	Sum of Squares	D O F	Mean Square	F Value	p-value Prob> F	
Model	1.371	6	0.228	807.077	< 0.0001	sig- nifi-cant
A- Taper Angle	0.002	1	0.002	8.271	0.0130	
B-Thick-ness	1.056	1	1.056	3728.971	< 0.0001	
C-Servo Voltage	0.261	1	0.261	921.488	< 0.0001	
AC	0.001	1	0.001	3.065	0.1036	
B^2	0.021	1	0.021	75.706	< 0.0001	
C^2	0.025	1	0.025	88.686	< 0.0001	
Residual	0.004	13	0.0002			
Lack of Fit	0.0007	8	.0001	0.159	0.988	not signif-icant
Pure Error	0.003	5	0.0005			
Cor Total	1.37	19				

Angular Error (AE)

It can be observed from the Fig.4 that, increase in taper angle leads to increase in angular error for workpieces of varying thick-ness. The stiffness of the wire and the forces exerted during the cutting process are the rea- sons leading to increase in angular error with increase in taper angle. An- gular error was high when taper angle and part thickness were at higher levels.

From Fig.5 it can be noted that the higher the part thickness is, higher the deviation from the nominal angle is obtained for parts with servo voltage 3V & 10V and a gradual increase in deviation was seen in piece with 20V, whereas angular error decreased dras-tically 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 be-tween 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.

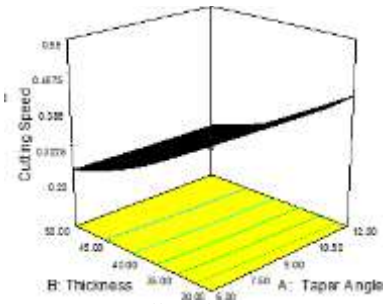


Fig. 1: Surface Plots Showing Effect of Taper Angle and Thickness on Cutting Speed.

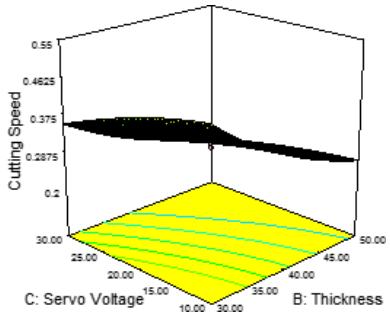


Fig. 2: Surface Plots Showing Effect of Servo Voltage and Thickness on Cutting Speed.

Fig.3 also demonstrates that increase in servo voltage resulting in decrease of cutting speed at corresponding taper angles. Higher the value for servo voltage, the wider the gap between the work piece and the wire (electrode) becomes, which leads to decrease in the number of electric sparks resulting in increase in machining time and decrease in cutting speed.

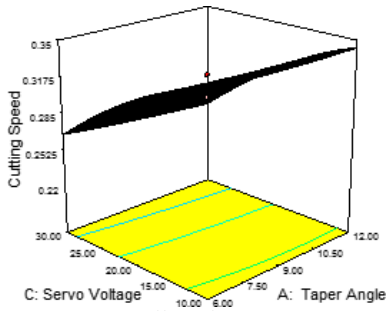


Fig. 3: Surface Plots Showing Effect of Servo Voltage and Taper Angle on Cutting Speed.

From the Fig.6 , it can be seen that the increase in servo voltage leads to drastically decrease in angular error for parts with angle 4° & 6° and a gradual decrease in deviation was seen in piece with angle 9°, whereas angular error increased for the parts with 12°&14° for different servo voltage values. For the pieces with higher taper angle (12°&14°) the con- tact length between wire and guides will be more with high axial force acting on the wire and when the servo voltage is lesser the gap between the work piece and the wire becomes narrow, which leads to increase in the number of repetitive electric sparks making the state of machining at the gap unstable resulting in increase in angular error. For the pieces with lower taper angles (4°, 6°&9°), less forces will be acting on the wire and the angular error will be decreased with increase in servo voltage.

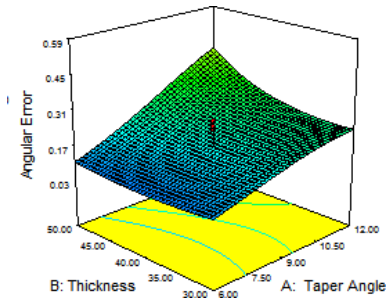


Fig. 4: Surface Plots Showing Effect of Taper Angle and Thickness on Angular Error.

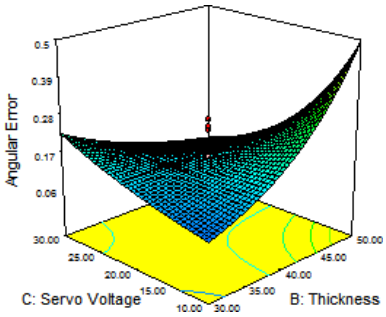


Fig. 5: Surface Plots Showing Effect of Servo Voltage and Thickness on Angular Error.

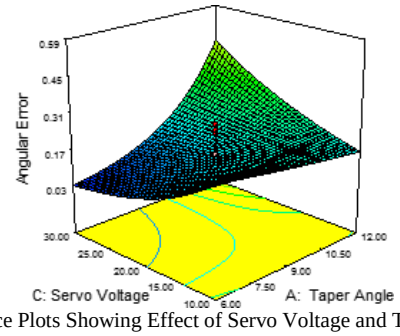


Fig. 6: Surface Plots Showing Effect of Servo Voltage and Taper Angle on Angular Error.

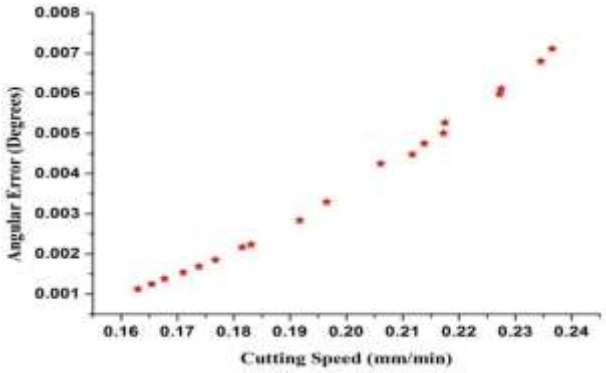


Fig. 7: Pareto Optimal Front.

6. Multi objective optimization

Optimized Pareto front with incompatible responses maximizing cutting speed and minimizing angular error are marked along the x-axis and the y- axis, each after 126 repetitions as shown in the Fig.7. The weighted aver- age of the fitness function for 75 generations was used as a criterion to stop the algorithm. Any point in the Pareto set is related with a set of deci- sion variables. Particular star marks between these axes represent a non- dominated solution between permissible Pareto optimal of all the star points of the Pareto front. All Pareto solutions were optimal solutions. The population size is 75. The multi objective genetic algorithm uses the tour- nament selection by size 2, adaptive feasible mutation and scattered cross- over.

In addition, optimum process parameters that satisfy both objective func- tions in maximizing cutting speed and minimizing error are utilized in a set of experiments. At first, a set of process parameters is employed (4.5 taper angle , 50.37 mm thickness and 36 v of servo voltage) which is found optimum for obtaining maximum cutting speed as shown. Another set is employed with set (6.64 taper angle, 43.34 mm thickness and 30.65 volts servo voltage) which is determined to be an optimum set for minimizing angular error equally as shown. Finally, another set of optimum process parameters for maximizing cutting speed and minimizing angular error (13.96 taper angle, 23 mm thickness and 3 volts servo voltage) is utilized in Fig. 6.

7. Conclusions

Based on response surface model, the results in terms of effect of taper angle, part thickness & servo voltage on cutting speed and angular error respectively were concluded as Angular error was increased with increase in taper angle. As part thickness increased AE increased for pieces with SV 3V, 10V & 20V and decreased rapidly for pieces with SV 30V & 37V. With increase in SV, AE increased for work pieces with taper angle 12°&14°, de- creased gradually for piece with taper angle 9° and decreased sharply for pieces with taper angle 4°& 6°.

Part thickness was found to be the most significant parameter effect- ing angular error followed by servo voltage and it was evident that the taper angle was the least significant parameter effecting angular error.

Set of optimum process parameters for maximizing cutting speed and minimizing angular error is 13.96 taper angle, 23 mm thickness and 3.

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