Multi-Parametric Optimization of WEDM Process Using Desirability Function Analysis

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Abstract: The present research study deals the Wire electrical discharge machining (WEDM) process for High carbon high-chromium steel (D3) with multi-parametric optimization based on the Taguchi method and desirability function analysis. Experiments were carried out based on an L9 orthogonal array. The effect of process parameter such as pulse-on time (Ton), pulse-off time (Toff), current (IP) and wire speed (Ws) were analyzed on the performance measures such as material removal rate, dimensional deviation, gap current and machining time. The optimum cutting conditions are obtained by Taguchi method and desirability function. The analysis of variance (ANOVA) is applied to investigate the effect of input process parameters. Finally, the confirmation experiment was carried out for the optimal machining parameters, and the betterment has been proved.

Keywords: D3 tool steel, Desirability Function Analysis (DFA), Multi-parametric optimization, Wire Electrical Discharge Machining (WEDM).

I. INTRODUCTION

In mechanical industry, the demands for alloying materials having High Strength, High Hardness, High Thermal Resistance, High Abrasive Wear, more toughness, high impact resistance are increasing but, these materials are difficult to be machined by traditional machining methods. Hence, non-traditional machining methods including electrochemical machining, ultrasonic machining, electrical discharging machine (EDM) etc. are applied to machine such difficult to machine materials. WEDM is one of the most popular in all conventional EDM process, which used a wire electrode to initialize the sparking process.

In WEDM Process a small diameter wire range from 0.05 to 0.3 mm (Rao 2011) is applied as the tool electrode. The wire is continuously supplied from the supply spool (Fig. 1), through the work-piece, which is clamped on the table by the wire traction rollers. A gap of 0.025–0.05 mm is maintained constantly between the wire and work-piece. De-ionized water is applied as the dielectric fluid. A collection tank which is located at the bottom is used to collect the used wire and then discard it.

Due to the variation in dimensional accuracy wire which once used cannot be reused again. The dielectric fluid is continuously flashed through the gap along the wire, to the sparking area to remove the byproducts formed during the erosion (Kalpakjian and Schmid 2009).The WEDM is a well-established machining option for manufacturing geometrically complex or hard material parts that are extremely difficult-to-machine by conventional machining processes.
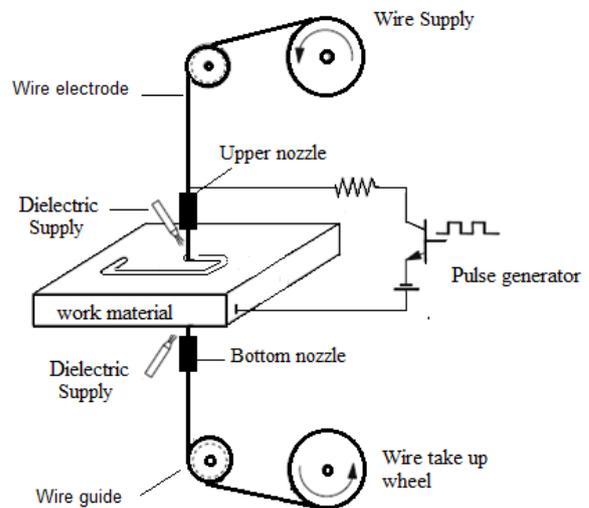
Fig 1: Representation of WEDM process

II. EARLY DEVELOPEMENT

In present work, the experiments were carried out on a WEDM machine (ELCTRONICA EL-CUT 334) of "Electronica Machine Tools Ltd. India". AISI D3 tool steel containing chemical composition C,2.25;Si,0.60,Mn,0.60;Cr,12;Ni,0.30;W,1;V,1;Cu0.25;P,0.03;S,0.03 having 30 mm thickness has been selected as workpiece material. Using WEDM, work material was machined and samples were obtained in the form of rectangular punch of profile of 20 mm × 20 mm square.
In cutting operation, process parameters namely pulse-on time (Ton), pulse off time (Toff), Current and wire speed

have been selected and Molybdenum wire having a fixed diameter of 0.18 mm has been selected as wire electrode. All cutting operation was conducted at zero wire offset setting. Distilled water having conductivity 20 mho has been utilized in the present study. High flow rate of dielectric results in complete and quick flushing of the melted debris out of the spark gap which results in high machining rate and good surface finish. Therefore, dielectric flow rate was kept at high value of 15 liters per minute. For this study four machining performance has been investigated namely Material removal rate, dimensional deviation, gap current and machining time. As already reported, for the present work, four process parameters each at three levels have been decided (Table: 1).The selection of a particular orthogonal array is based on the number of levels of various parameters. Now the Degree of Freedom (DOF) can be calculated by the Eq.1.

$$(DOF)R = P \times (L - 1) \qquad (1)$$

Where,

$(DOF)R$ = degree's of freedom

P = number of parameters

L = number of levels of each parameter

$$(DOF)R = 4 \times (3 - 1) = 8$$

However, total DOF of the orthogonal array (OA) should be greater than or equal to the total DOF required for the experiment, here DOF for OA is 8 and DOF for experiment is also 8, means condition is satisfied therefore L9 (34) orthogonal array is selected to assign various columns, the experiments were performed according to the trial condition as per L9 OA as shown in Table 2 and result data is presented in it.

Table: 1 Level values of process parameters

Sr.	Parameters	Unit	Level	Level	Level
1	Pulse on	μs	3	6	9
2	Pulse off	μs	2	4	6
3	Peak	Amp	1	2	3
4	Wire speed	m/min	3	5	7

Table: 2 L9 Design matrix with experiment Results

Ex. No.	Pulse on-time (T_{on})	Pulse-off time (T_{off})	Current (I_P)	Wire speed (Ws)	MRR gms/min	Dim. Deviation %	Gap current	Machining time. min
E 1	3	2	1	3	17.7	1.655	0.5	135.62
E 2	3	4	2	5	28.6	1.667	1.3	83.98
E 3	3	6	3	7	29.5	1.825	1.4	81.37
E 4	6	2	2	7	38.4	1.742	1.7	62.51
E 5	6	4	3	3	40.1	1.697	2.0	59.86
E 6	6	6	1	5	21.1	1.595	0.6	113.84
E 7	9	2	3	5	59.5	1.708	2.2	40.34
E 8	9	4	1	7	22.2	1.672	0.7	108.12
E 9	9	6	2	3	36.4	1.702	1.7	65.94

III.DESIRABILITY FUNCTION ANALYSIS (DFA)

The desirability function approach to optimize multiple equations simultaneously was originally proposed by Harrington [19].Essentially, the approach is to translate the functions to a common scale [0, 1], combine them using the geometric mean and optimize the overall metric. The desirability approach involves transforming each estimated response, yi, into a unit less utility bounded by 0<di<1, where a higher 'di' value indicates that response value yi is more desirable, if di=0 this means a completely undesired response [20].The steps involved in the optimization process are detailed below.

Step-1: The first step involves the calculation of desirability index (di) for each of the factors viz., MRR, Dimensional deviation, gap current and machining time. It is calculated based on the desirability piece wise function which is shown in Eq.2 and Eq. 3, respectively for the cases of larger the better and smaller the better.

i) Larger the better

$$d_i = 0, \qquad y_i \leq low_i$$
$$d_i = \left[\frac{y_i - low_i}{high_i - low_i}\right]^{wt_i}$$
$$low_i < y_i < high_i \qquad (2)$$
$$d_i = 1$$
$$y_i > high_i$$

The value of 'yi' is expected to be the larger the better. When the 'y' exceeds a particular criteria value, which can be viewed as the requirement, the desirability value equals to 1; if the 'y' is less than a particular criteria value, which is unacceptable, the desirability value equals to 0.

ii) Smaller the better

$$d_i = 1,$$
$$y_i \leq low_i$$
$$d_i = \left[\frac{high_i - y_i}{high_i - low_i}\right]^{wt_i}$$
$$low_i < y_i < high_i \qquad (3)$$

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$$d_i = 0$$
$$y_i > high_i$$

The value of 'yi' is expected to be the smaller the better. When the 'y' is less than a particular criteria value, the desirability value equals to 1; if the 'y' exceeds a particular criteria value, the desirability value equals to 0
In this study, "larger the better" and "smaller the better" characteristics are applied to determine the individual desirability values for maximize the MRR and gap current while for minimize the dimensional deviation and machining time.

Step-2: The second step is to evaluate the composite desirability based on the Eq.4

$$d_G = (d_1 \times d_2 \times ... \times d_n)^{\frac{1}{n}} \qquad (4)$$

Where, n is the number of responses in the measure. If any of the responses or factors falls outside their desirability range, the overall function becomes zero.

Step-3: The third step is to determine the optimal parameter and its level combination. The higher composite desirability value implies better product quality.

Therefore, on the basis of the composite desirability (dg), the parameter effect and the optimum level for each controllable parameter are estimated

Step-4: Perform ANOVA for identifying the significant parameters. ANOVA establishes the relative significance of parameters. The calculated total sum of square values is used to measure the relative influence of the parameters.

Step-5: Calculate the predicted optimum condition. Once the optimal level of the design parameters has been selected, the final step is to predict and verify the quality characteristics using the optimal level of the design parameters.

IV. RESULTS AND DISCUSSION

1. Steps in Desirability approach and ANOVA
Step1: The values of computed individual desirability for each quality using Eq. 2 and 3 were presented in Table 3.

Step2: The composite desirability values [dg] are calculated using Eq.4 The equal weightage of 0.25 was considered for all parameters and the calculated results are also given in Table 3.

Table: 3 Calculation of Overall Desirability

Ex No.	Individual desirability (Di)				Composite desirability (dg)
	MRR gms/min	Dim. Deviation	Gap current	Machining time min	
1	0.0000	0.7391	0.0000	0.0000	0.0000
2	0.2607	0.6869	0.4705	0.5419	0.4623
3	0.2822	0.0000	0.5294	0.5693	0.0000
4	0.4952	0.3608	0.7058	0.7673	0.5577
5	0.5358	0.5565	0.8823	0.7951	0.6763
6	0.0813	1.0000	0.0588	0.2285	0.1818
7	1.0000	0.5086	1.0000	1.0000	0.8445
8	0.1076	0.6652	0.1176	0.2886	0.2220
9	0.4473	0.5347	0.7058	0.7313	0.5928

Step 3: In this step, the main parameter effects are calculated and tabulated in Table 4. The factor effects are plotted in Fig.2 which shows the main effects plot for the composite desirability for the different levels of the Processing parameters. Basically, the larger the composite desirability, the better is the multiple performance characteristics. However, the relative importance among the parameters for the multiple performance characteristics will still need to be known so that the optimal combinations of the process parameter levels can be determined more accurately.

Table 4: Response Table for composite desirability

Levels	Pulse on Time (Ton)	Pulse off Time (Toff)	peak current (Ip)	wire speed (Ws)
1	0.1541	0.4674	0.1346	0.4230
2	0.4719	0.4535	0.5376	0.4962
3	0.5531	0.2582	0.5069	0.2599
Max- Min	0.399	0.2092	0.403	0.2363
Ranking	2	4	1	3
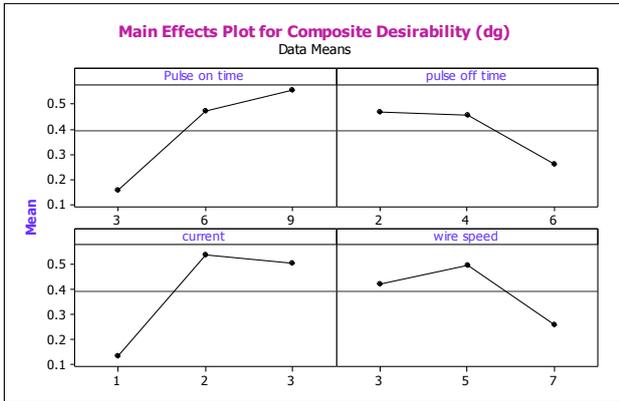
Fig: 2 Main effect plots for composite desirability index

Step 4: From Table 4 and Fig. 2, the optimum setting parameters such as A3B1C2D2 are obtained and also observed that, there is one particular level for each factor for which the responses are either maximum or minimum. To test the optimum setting values of desirability approach, experiments are conducted in WEDM by using the input parameters through desirability approach and corresponding outputs values of shown in Table 6. When comparing these values with initial setting obtained in the L9 array of experiments, the desirability approach gives optimum result for all responses in one set of input.

Step 5. The calculated results of ANOVA are presented in Table 3.

$$\eta_{opt} = 0.3930 + (0.5531 - 0.3930) \\ + (0.4674 - 0.3930) \\ + (0.5376 - 0.3930) + (0.4962 \\ - 0.3930)$$
$$\eta_{opt} = 0.875$$

Table: 5 ANOVA table

Parameter	Degree of freedom	Seq. sum of square	Adj.sum of square	Adj. Mean square (Variance)	% Contribution (P)
Pulse on time	2	0.266807	0.266807	0.133404	36.11
Pulse off time	2	0.082112	0.082112	0.041056	11.11
peak current	2	0.301982	0.301982	0.150991	40.87
wire speed	2	0.087804	0.087804	0.043902	11.88
Total	8	0.738704			

Table: 6 Predicted and experimental values

Sr. No.	Machining characteristics	Initial setting	Predicted value	Experimental value
1	Optimum setting parameter	A3B1C3D2	A3B1C2D2	A3B1C2D2
2	MRR	59.5		58.5
3	Dimensional deviation	1.70		1.69
4	Gap current	2.2		2.1
5	Machining time	40.34		41.00
6	Composite desirability value (dg)	0.8445	0.8753	0.8553
Improvement in Composite desirability value (dg) =1.09 %				

IV. CONCLUSIONS

This work presents the experimental study on wire electrical discharge machining of Monel-400, a nickel–copper based alloy. Using desirability function, a scale-free quantity called desirability has been obtained for two performance characteristics to optimize multi-performance characteristics, i.e., MR and SR. Corresponding to highest desirability, the optimal combination of process parameters were Ip: 103 A; Ton: 113 ls; Toff: 37 ls and SV: 50 V. Trim cutting operations at low discharge energy (Ton: 105 ls; Toff: 35 ls; Ip: 90 A; SV: 30 V) and different wire offset values (105 and 85 lm) were performed after a single rough cut at high discharge energy. Results showed that using single trim cut at low discharge energy and appropriate wire offset value, surface integrity of work material can be improved successfully.

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