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Multi Objective Optimization of WEDM through Taguchi Method and Utility Concept

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Abstract*:* The present study highlights a multi objective optimization approach to determine the optimal process parameters in wire electrical discharge machining process. Experiments have been conducted using 3 machine parameters such as pulse on time (TON), pulse off time (TOFF), wire feed (WF) and one work piece parameter such as work piece thickness, each at three levels for obtaining the responses like cutting speed, surface roughness, and dimensional deviation. Taguchi's L_9 orthogonal array is used to gather information regarding the process with less number of experimental runs. Traditional Taguchi approach is insufficient to solve a multi response optimization problem. In order to overcome this limitation, utility theory has been implemented, to convert multi-responses into single equivalent response called overall utility index. The weight for each criterion (response) is obtained using intuition and judgement of the decision maker.ANOVA analysis is also carried out to find out the significant effect of the process parameters during WEDM process.Finally confirmation test has been carried out to verify the result.

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Key words: WEDM, Utility conept, Taguchi Method, ANOVA.

INTRODUCTION

The recent trend of manufacturing industries in achieving larger quantities with good quality product is embarked by employing non traditional machine tools in order to obtain tight tolerances and accurate dimensions in shortest time possible to make their products timely in the market. One of the ways to achieve these instant manufacturing practices is by simulating the processes to its actual conditions before they are put onto the actual production floor. High number of simulation tools are being employed for this reasons as the method is seen to be more reliable as compared to the traditional trial and error methods.

Optimization of process parameters is an important criterion in the machining process to achieve high quality. Normally, the Taguchi method is used to optimize the performance characteristics of process parameters to achieve high quality [1, 2]. However, most reports on Taguchi applications to date have been concerned with the optimization of a single performance characteristic [3]. Handling the more demanding multiple performance characteristics are still an interesting research problem. Optimization of multiple response characteristics is more complex compared to optimization of single performance characteristics [4, 5]

The Taguchi method can optimize performance characteristics through the settings of process parameters and reduce the sensitivity of the system performance to sources of variation. As a result, the Taguchi method has become a powerful tool in the design of experiment methods [9]. However, Taguchi method fails to solve multi objective optimization problems.To overcome this shortcoming, in the present work, Utility concept has been explored to aggregate multiple responses (objective functions) into an equivalent quality index (single objective function). The overall utility index has been optimized (maximized) finally by Taguchi method.However Utility concept requires the priority weight of each response to calculate the overall utility index. Hence, in the present work, the weight for each criterion (response) is obtained by intuition and judgment of the decision maker. ANOVA analysis is also carried out to find out the significant effect of the process parameters in WEDM process. Finally, a confirmatory test has been carried out to verify the optimal setting so obtained.The results from the confirmation runs indicate that the determined optimal combination of machining parameters improves the performance of machining process.

PROPOSED METHODOLOGY

Utility can be defined as the usefulness of a product or a process in reference to the levels of expectations to the consumers. The performance evaluation of any machining process depends on number of output characteristic. Therefore, a combined measure is necessary to gauge its overall performance, which must take into account the relative contribution of all the quality characteristics. Such a composite index represents the overall utility of a product/process. It provides a methodological framework for the evaluation of alternative attributes made by individuals, firms and organizations. Utility refers to the satisfaction that each attributes provides to the decision maker. Thus, utility theory assumes that any decision is made on the basis of the utility maximization principle, according to which the best choice is the one that provides the highest satisfaction to the decision maker [8]

According to the utility theory [9,10] if X_i is the measure of effectiveness of an attribute (or quality characteristics) i and there are n attributes evaluating the outcome space, then the joint utility function can be expressed as:

$$U(X_1, X_2,......X_n) = f(U_1(X_1),U_2(X_2),.....,U_n(X_n)) \quad (1)$$

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Here, *Ui (Xi)* is the utility of the i^{th} attribute.

The overall utility function is the sum of individual utilities

if the attributes are independent, and is given as follows:

$$U(X_1, X_2, ...X_n = \sum_{i=1}^{n} U_i(X_i). \qquad (2)$$

The overall utility function after assigning weights to the attributes can be expressed as:

$$U(X_1, X_2, ...X_n) = \sum_{i=1}^{n} W_i.U_i(X_i) \qquad (3)$$

The preference number can be expressed on a logarithmic

scale as follows:

$$P_i = A \times \log\left(\frac{X_i}{X_i^{'}}\right) - - - - - (4)$$

Here, X_i is the value of any quality characteristic or attribute i, $X_i^{'}$ is just acceptable value of quality characteristic or attribute i and A is a constant. The value A can be found by the condition that if $X_i = X^*$ (where X^* is the optimal or best value), then $P_i = 9$ Therefore,

$$A = \frac{9}{\log \frac{X^*}{X_i^{'}}} \quad \text{-------------- (5)}$$

The overall utility can be expressed as follows:

$$U = \sum_{i=1}^{n} W_i P_i \quad \text{-------------- (6)}$$

Subject to the condition:

$$\sum_{i=1}^{n} W_i = 1 \qquad (7)$$

Overall utility index that has been computed treated as a single objective function for optimization. Among various quality characteristics types, viz. Lower-the-Better (LB), Higher-the-Better (HB), and Nominal-the-Best (NB) suggested by Taguchi, the utility function would be higher. In the proposed approach utility values of individual responses are accumulated to calculate overall utility index. Overall utility index servers as the single objective function for optimization.

However in the proposed work, the associate weight for each response required for calculation of overall utility index is considered equally for all responses.

The multi-characteristic optimization algorithm

In this paper, the following algorithm is suggested based on Taguchi's technique and utility concept.

- Find optimal values of the selected quality characteristics separately usingTaguchi experimental design and analysis.
- Using the optimal values and the minimum quality levels for the characteristics from the experimental data, construct preference scale for each quality characteristic.
- Assign weightsW_i, i = 1,2, . . . , n based on experience and end use of the product such that equation (7) is satisfied.
- Find utility values for each product against each trial condition of the experiment using equation (6).
- Use these values as a response of the trial conditions of the selected experimental plan.
- Analyze results using the procedure suggested by Taguchi (Roy, 1990).
- Find the optimal settings of the process parameters for optimum utility (mean and minimum deviation around the mean) based on the analysis.
- Predict the individual characteristic values considering the optimal significant parameters determined.
- Conduct confirmation experiment at the optimal setting and compare the predicted optimal values of the quality characteristics with the actual ones.

The flow chart of the methodology is shown in Fig 1.

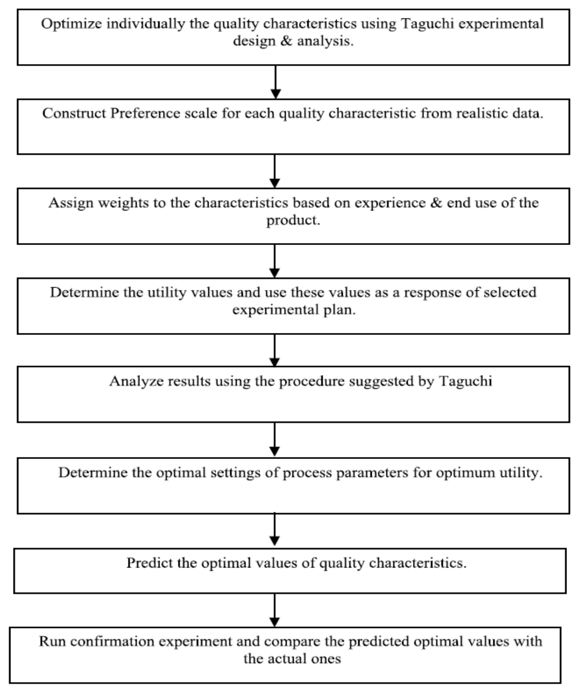

Fig 1: Flow chart of proposed algorithm for simultaneous optimization of multiple responses

WIRE ELECTRICAL DISCHARGE MACHINING PROCESS

Wire-cut electrical discharge machining (WEDM) has grown tremendously since it was first applied more than twenty years ago. Its broad capabilities have allowed it to encompass the production, aerospace/aircraft and medical industries and virtually all areas of conductive material machining. As newer and more exotic materials are developed, and more complex shapes are presented, conventional machining operations will continue to reach their limitations and the increased use of wire EDM in manufacturing will continue to grow at an accelerated rate

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[11]. In the WEDM process, a small wire is engaged as the tool electrode. The dielectric medium, which is usually de ionized water, does not immerse the wire. The work piece is mounted on the table of the machine and the dielectric medium is ejected to the sparking area. The movement of the wire is controlled numerically to achieve the desired complex two- and three-dimensional shapes for the work piece. What wire-cut EDM manufacturers and users want is to achieve higher machining productivity with a desired accuracy and surface finish? However, due to a large number of variables and the stochastic nature of the process, even a highly skilled operator with a state-of the- art WEDM is rarely able to achieve the optimal performance [12]. An effective way to solve this problem is to determine the relationship between the performance of the process and its controllable input parameters (i.e. model the process through suitable mathematical techniques). Investigations into the influences of machining input parameters on the performance of EDM and WEDM have been reported widely [12 -16] and several attempts [17-19] have been made to model the process.

In wire-cut EDM process the spark is occurring between continuous travelling wire and work piece. Here wire acts like a band saw, but sparks instead of teeth do the cutting. The variations in the machining parameters, such as the pulse on time, pulse off time, wire feed rate, and work piece thickness greatly affect the measures of the machining performance, for example, the SR, cs and the DD. Therefore, proper selection of the machining parameters can result in better machining performance in the wire electrical discharge machining process.

Experimental set up and Experimental Procedure

The experiments were carried out on EZEECUT NXG CNC WEDM machine. In this machine, all the axes are servo controlled and can be programmed to follow a CNC code which is fed through the control panel. All three axes have an accuracy of 1µm. The electrode material used was a 0.25 mm diameter brass wire. Wire-cut electrical discharge machining of Inconel825 alloy has been considered in the present set of research work.

The size of the work piece considered for experimentation on the wire-cut EDM is 10 mm width, 10 mm length and 15 mm depth of cut. According to the Taguchi method based on robust design a L_9 (4^3) orthogonal array is employed for the experimentation.

In setting the machining parameters, particularly in rough cutting operation, the goal is threefold - the maximization of CS, minimization of SR and minimization of dimensional deviation. Generally, the machine tool builder provides machining parameter table to be used for setting machining parameter. This process relies heavily on the experience of the operators. In practice, it is very difficult to utilize the optimal functions of a machine owing to there being too many adjustable machining parameters. With a view to alleviate this difficulty, a simple but reliable method based on statistically designed experiments is suggested for investigating the effects of various process parameters on CS, SR and DD determines optimal process settings. Finally, utility concept with Taguchi technique has been adopted to evaluate the optimal process environment.

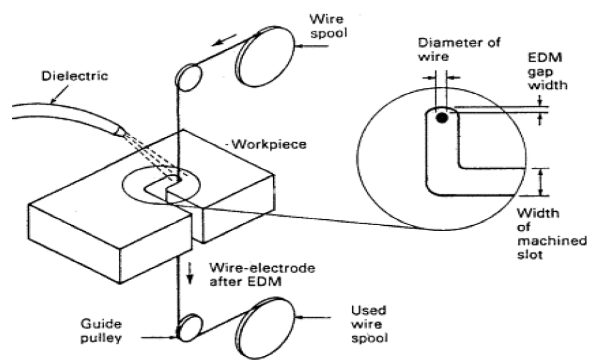

Fig 2. Schematic diagram of WEDM

Machining parameters and their levels for WEDM machining

The selection of optimum machining parameters in WEDM is an important step. Improperly selected parameters may result in serious problems like short-circuiting of wire, wire breakage and work surface damage which is imposing certain limits on the production schedule and also reducing productivity. As cutting speed (CS), surface roughness (SR) and dimensional deviation (DD) are most important responses in WEDM; various investigations have been carried out by several researchers for improving the CS, Surface Finish and dimensional accuarcy [3–7]. However, the problem of selection of machining parameters is not fully depending on machine controls rather material dependent.

To perform the experimental design, the levels of machining parameters are selected as in Table 1.

Table 1: Process parameters and their levels for WEDM

Symbol	Control Factor	Level-1	Level-2	Level-3
A	WorkPiece Thickness(mm)	6	10	15
B	Pulse On Time(µs)	32	45	60
C	Pulse off Time(µs)	2	4	6
D	Wire Feed(mm/min)	75	88	99

Measurement of response characteristics

The multiple responses from the experiment were calculated as follows.

Cutting speed is measured in mm/min from control panel of WEDM machine.

Surface roughness is measured with surfcorderSE3500 in µm and dimensional deviation is measured with micrometer in mm. The experimental results are presented in Table 2.

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Table 2: Experimental results form WEDM

Exp. run	A	B	C	D	CS (mm/min)	SR (µm)	DD (mm)
1	1	1	1	1	3.96	9.23	0.25
2	1	2	2	2	3.34	9.34	0.37
3	1	3	3	3	3.80	9.24	0.24
4	2	1	2	3	3.06	6.14	0.27
5	2	2	3	1	2.94	8.27	0.23
6	2	3	1	2	2.91	6.72	0.20
7	3	1	3	2	1.89	5.07	0.30
8	3	2	1	3	1.91	6.95	0.25
9	3	3	2	1	2.57	6.29	0.53

ANALYSIS OF RESULTS

Using Taguchi's analysis and the ANOVA, the optimal settings of turning process parameters for CS, SR and DD were obtained separately and the optimal values of the selected characteristics were predicted. The average values of the machiningcharacteristics at each level and against each parameter were calculated and are reported in Table 3. The summary results are given in Table4.

Table 4 displays the individual optimal values of the selected characteristics and corresponding optimal settings of the process parameters for WEDM of Inconel 825.

Table 3: Average values of response characteristics at different levels

Process Parameter	CS			SR			DD		
	L-1	L-2	L-3	L-1	L-2	L-3	L-1	L-2	L-3
A	3.7	2.97	2.12	9.27	7.04	6.10	0.28	0.23	0.36
B	2.97	2.73	3.09	6.81	8.18	7.42	0.27	0.28	0.32
C	2.92	2.99	2.88	7.63	7.26	7.53	0.23	0.39	0.25
D	3.16	2.71	2.92	7.93	7.04	7.45	0.33	0.29	0.25

Table 4: Optimal settings of process parameters and optimal values of individual quality characteristics

Respponse characteristic	Optimal setting of process parameter	Predicted
Cutting Speed(mm/min)	A1B3C2D1	3.85461
Surface roughness(µm)	A3B1C2D2	5.0793
Dimensional deviation(mm)	A2B1C1D3	0.22

Preference scale construction

Cutting Speed

X^*= optimum value of CS= 1.89 mm/min (refer to Table IV)

X^1= minimum acceptable value of CS=3.96 mm/min (assumed, as all the observed values of CS in Table II are in between 1.89 and 3.96mm/min)

Using these values and the equations (4) and (5), the preference scale for CS was constructed as

P_{CS}= 29.1272 log [X_{CS}/1.89] -------- (8)

Surface roughness

X^*= optimum value of SR=5.0793 µm (refer to Table IV)
X^1= minimum acceptable value of CS=9.34 µm (assumed, as all the observed values of CS in Table II are in between 5.07 to 9.34 µm)

Using these values and the equations (4) and (5), the preference scale for SR was constructed as

P_{SR}= -34.02 log [X_{SR}/9.34] -------- (9)

Dimensional Deviation

X^*= optimum value of DD=0.22mm (refer to Table IV)

X^1= minimum acceptable value of DD=0.53 mm (assumed, as all the observed values of CS in Table II are in between 0.23 and 0.53mm)

Using these values and the equations (4) and (5), the preference scale for DD was constructed as

P_{DD}= -23.5692 log [X_{DD}/0.53] -------- (10)

Weight of quality characteristics

The weights to the selected quality characteristics were assigned as given below:

W_{CS}=Weight assigned to cutting speed=1/3
W_{SR}=Weight assigned to surface roughness=1/3
W_{DD}= Weight assigned to dimensional deviation=1/3

It has been assumed that all the response characteristics are equally important and hence equal weights have been assigned. However, there is no constraint on the weights and it can be any value between 0 and 1 subject to the condition specified in equation (7).

The customers' requirements and priorities should be taken into consideration while deciding the weights of response characteristics.

Utility value calculation

The utility value of each turned part was calculated using the following relation (overall utility function):
U (n, R) = P_{CS}x W_{CS}+ P_{SR}x W_{SR}+ P_{DD}x W_{DD}………….(11)
Where, n = trial number,
n =1, 2. . . 27;
R = replication number, R = 1, 2, 3
The utility values thus calculated are reported in Table V.

Analysis of the data and determination of optimal settings of process parameters

The data (utility values) were analyzed both for mean response (mean of utility at each level of each parameter) and signal-to-noise (S/N) ratio. Since utility is a "higher the

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better" (HB) type of characteristic, (S/N)HB has been used (Ross, 1996):

$$\text{S/N Ratio} = -10\log_{10}(1/n)\sum_{i=1}^{n}\frac{1}{y_{ij}^{2}} \qquad (12)$$

Where, yj =value of the characteristic at observation j; R= number of replications in a trial.

The S/N ratios are also given in Table 5. The mean responses and main effects in terms of utility values are calculated and reported in Table 6.

Table 5: Utility data based on response characteristics

Exp No.	UCS	USR	UDD	U overall	S/N ratio Uoverall
1	9.54	0.17	7.691	5.800333	15.2691
2	7.19	0.0063	3.6785	3.624933	11.1860
3	8.83	0.14	8.1093	5.6931	15.1070
4	6.10	6.17	6.9037	6.391233	16.1117
5	5.61	1.79	8.544	5.314667	14.5095
6	5.44	4.84	9.975	**6.751667**	**16.5882**
7	0.00	9.00	5.8252	4.941733	13.8776
8	0.12	4.35	7.6914	4.0538	12.1572
9	3.91	5.83	0	3.246667	10.2288

Table 6: Response table for S/N ratios of utility values

Level	A	B	C	D
1	13.8540	15.0861	14.6715	13.3358
2	15.7365	12.6176	12.5088	13.8839
3	12.0879	13.9747	14.4980	14.4586
Rank	1	2	3	4

Table 7: Response table for means of utility values

Level	A	B	C	D
1	5.03946	5.71110	5.53527	4.78722
2	6.15252	4.33113	4.42094	5.10611
3	4.08073	5.23048	5.31650	5.37938
Rank	1	2	3	4

The average values of S/N ratios are reported in Table 7. The data from Tables 6 and 7 are plotted in Fig 3 and Fig 4.

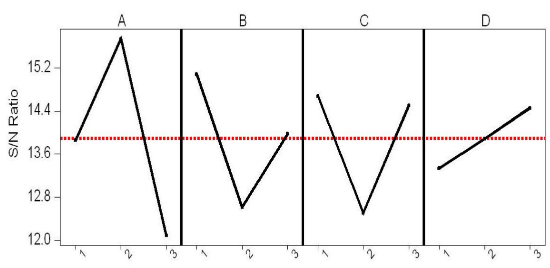

Fig 3: Main effects of parameters on means of Utility overall value

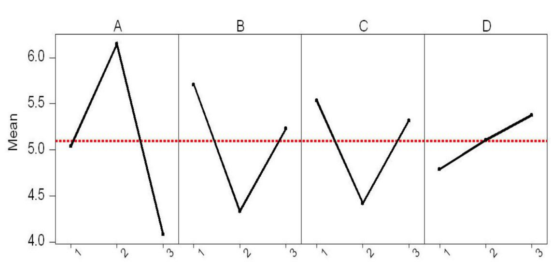

Fig 4: Main effects of parameters on S/N ratios of Utility overall value

It is clear from the Fig 4 that the second level of cutting speed (A2), the first level of oulse on time (B1), first level of pulse off time (C1) and third level of wire feed (D3) would yield best performance in termsof utility value and S/N ratio within the selected range of parameters.

The ANOVA for raw data (utility) and S/N ratio are given in

Tables 8 and 9 respectively. It is clear from the Tables 8 and 9 that thickness of the work piece (A) is showing 50% contribution on responses follwoed by pulse on time (25%), pulse off time (20%) and wire feed (5%)

Table 8, 9 also reveals that the contribution of work piece thickness is significantly quite larger.

Table 8: Response table for means of utility values

ANOAV for means of overallUtility value					
Sourse	**DF**	**SS**	**MS**	**F**	**%**
A	2	6.45	3.225	4.93	53.68
B	2	2.94	1.472	2.25	24.47
C	2	2.09	1.045	0.45	17.39
D	2	0.53	0.265	0.11	4.41
Error	3	0.001			
Total	11	12.014			

Table 9: Response table for S/N ratos of utility values

ANOAV for S/N ratios of overallUtility value					
Sourse	**DF**	**SS**	**MS**	**F**	**%**
A	2	19.98	9.99	3.78	50.32
B	2	9.17	4.585	1.74	23.09
C	2	8.66	4.33	0.59	21.81
D	2	1.89	0.945	0.13	4.76
Error	3	0.001			
Total	11	39.70			

Confirmation Experiments

The confirmation test for the optimal parameter setting with its selected levels was conducted to evaluate the response characteristics for WEDM of Inconel825. Experiment 6 (Table 5) shows the highest utility value, indicating the optimal process parameter set of A2B3C1D2 has the best multiple performance characteristics among the nine experiments, which can be compared with results of confirmation experiment for validation of results. Table 10 shows the comparison of the experimental results using the orthogonal array (A2B3C1D2) and utility theory design optimal (A2B1C1D3) WEDM parameters on Inconel825. The response values obtained from the confirmation experiment are CS = 3.3 mm/min, SR = 6.3 µm and DD = 1.9 mm. The cutting speed shows an increased value of 2.91 mm/min to 3.3mm/min, the surface roughness shows a reduced value of 6.72 µm to 6.3 µm and the dimesional deviation shows a reduced value of 0.2 to 0.19 mm respectively. The corresponding improvement in cutting speed is 11.81%, surface roughness and dimensional deviation were 6.66%, and 5.3% respectively.

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Table 10: Response table for S/N ratos of utility values

Response parameters	Optimal process parameters	
	Predicted value	Actual value through Confirmation Experiment
CS(mm/min)	2.91	3.3
SR(μm)	6.72	6.3
DD(mm)	0.20	0.19

CONCLUSIONS

- It can be seen from the graph for CS to be maximum, factor A has to be at level 1, factor B has to be at level 3, factor C has to be at level 2 and factor D has to be at level 1.
- It can be seen from the graph for Surface Roughness to be minimum factor A has to be at level 3, factor B has to be at level 1, factor C has to be at level 2 and factor D has to be at level 2.
- It can be seen from the graph for Dimensional deviation for the minimum, factor A has to be at level 2 , factor B has to be at level 1, factor C has to be at level 1 and factor D has to be at level 3.
- According to the utility concept with taguchi technique we found that 6th experiment is giving the optimal values for CS, DD and surface roughness ie. A2, B3, C1, D2 has the best optimal performance characteristics among the 9 experiments conducted.
- The response table provides the basis to identify the optimal parametric combination for the performance characteristics. Based on the maximum values shown in the response table for different levels the optimal level of machining parameters is A2, B1, C1, and D3.
- From ANOVA table for means and S/N ratios for utility overall vales, it is showing that work piece thichness is showing maximum influence on performance of WEDM around 50% followed by pulse on time with 25%. Pulse off time 20% and 5% of wire feed on responses.

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