Manufacturing Review

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RESEARCH ARTICLE

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Multi-response optimization in wire electrical discharge machining (WEDM) of D₂ steel using utility approach

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Abstract. Wire electrical discharge machining (WEDM) is a popular non-conventional machining process used particularly for making extrusion dies, blanking punches, and tools especially requiring tight dimensional tolerances. Because of the process limitation, the rate of cutting and maintenance of close dimensional tolerance is a challenging task. Given the above facts, the present work has been focused on achieving the maximum possible cutting rate (V_C) maintaining good dimensional accuracy and corner radius (R_C). In the present research work, a multi-response optimization method (i.e. Taguchi based Utility approach) has been used to obtain an optimum set of input parameters such as pulse on time (T_{ON}), pulse off time (T_{OFF}), servo voltage (SV), and wire feed rate (WF) resulting into a best overall cutting performance. Analysis of variance (ANOVA) is also used to find out the significant effect of each machining parameter on the cutting performance. The analysis reported in this paper will be helpful for industry personnel to select the best set of process parameters for achieving a good result without the use of any software or statistical analysis.

Keywords: WEDM / utility approach / D₂ steel / orthogonal array / ANOVA

1 Introduction

The development of newer and exotic materials in the recent past has led to the extensive use of non-conventional processes as compared to conventional machining processes. Recently, the use of wire electrical discharge machining (WEDM) process has grown tremendously in the field of conductive material machining owing to its advantage of being unaffected by material hardness and the ability to cut complex shapes with high accuracy [1]. In WEDM, a thin wire made of copper, brass, or tungsten is engaged as a tool electrode. In this process, it is very difficult to achieve a high material removal rate with good dimensional accuracy. Utility theory was implemented by Nayak and Mahapatra to simultaneously optimize three performance characteristics, i.e. angular error, surface roughness, and cutting speed [2]. Experimental studies were carried out by Mathew et al. for optimizing multiple performance characteristics on WEDM of AISI 304 stainless steel by using the Taguchi-Utility approach [3]. Shivade and Shinde optimized MRR, dimensional deviation, gap current, and machining time of the WEDM process for AISI D₃ tool steel based on the GRA method [4]. Ugrasen et al. presented an effective approach to

finding out the optimum cutting condition to get the desired surface finish, volumetric MRR, and machining accuracy while machining HCHCr workpiece material. The process has been optimized by the Taguchi method [5]. Conde et al. studied different causes of dimensional deviations in small radius circles. Results showed that the concavity effect produced in the workpiece was mainly due to the wire lag phenomenon [6]. Dabade and Karidkar analyzed the machining conditions for MRR, surface roughness, kerf width, and dimensional deviation during WEDM of Inconel 718. They observed that pulse-on-time greatly affects all the response variables [7]. Garg and Sharma derived a mathematical model using the RSM technique to investigate the dimensional deviation induced by WEDM of ZrSiO₄P/6063 Aluminium metal matrix composite (MMC). Experiments have been conducted with four process parameters such as T_{ON}, T_{OFF}, peak current, and servo voltage. The desirability function approach has been adopted to find out the optimum process parameters [8]. Zhang et al. investigated the thermal deformation behavior during WEDM processing of three different materials, such as AISI H13, SKD11, and Inconel 718. Experimental results showed that input energy and process parameters, namely pulse-on-time, water pressure, and wire feed greatly affect the thermal deformation phenomenon. Microstructural study of the machined surfaces revealed that the surface

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integrity, recast layer thickness, and heat-affected zone thickness varies with the magnitude of thermal deformation [9]. Mouralova et al. focused on the effect of different machining parameters (e.g. gap voltage, pulse on and off time, discharge current, and wire feed) on the machined surface quality of pure aluminum 99.5. Morphological analysis done by scanning electron microscopy (SEM) showed that the machined surface of each sample was covered with craters and recast layer of varied thickness [10].

The box-Behnken design approach of response surface methodology (RSM) was used by Chaudhari et al. to analyze the effect of pulse on time, pulse off time, and current on different machining characteristics such as material removal rate and micro hardness of shape memory alloy. They adopted heat transfer search algorithm for predicting and optimizing the input parameters and the results were validated through confirmatory experiments [11]. Many research works have been done on the machining of superalloy, composites, nickel-based alloy, Ti-6Al-4V, SiC, and Aluminium reinforced composites by using the wire EDM process. From the experimental studies, it was observed that surface finish in WEDM gets better with increasing pulse-off time and servo voltage [12,13]. It was also found that most of the studies have been carried out for the optimization of MRR, surface roughness of different materials, whereas some performance characteristics such as gap current, dimensional deviation, micro hardness are least focused [14,15]. Impacts of WEDM machining parameters on MRR and R_a for Magnesium metal matrix composite was investigated by Kavimani et al. by using Taguchi coupled GRA multi-objective optimization technique. Experimental results of this study revealed that MRR and R_a increase appreciably with the increase in pulse on time [16]. Singh et al. used RSM based Box-Behnken design model to optimize WEDM process parameters such as pulse on time, pulse off time, servo voltage, and peak current during machining of Nimonic 75 alloy. Quadratic regression models developed for response characteristics (i.e. material removal efficiency and kerf width) were validated through confirmatory experiments [17]. Priyadarshini et al. employed a hybrid multi-objective optimization technique i.e. Fuzzy- Technique for Order Preference by Similarity to Ideal solution (TOPSIS) to attain optimum cutting condition for higher MRR and lower kerf width during the machining of AISI P20 tool steel [18].

It is evident from the literature that very few authors have conducted multi-response optimization of D_2 tool steel in WEDM least focusing on machining accuracy i.e. dimensional accuracy which is of prime importance while producing mould and die cavities. D_2 steel is high carbon high chromium (HCHCr) tool steel and it has a wide range of applications in almost all industries owing to its high corrosion resistance property. In the present work, Taguchi's design of experiment is used for investigating the effect of various process parameters on cutting rate (V_C), dimensional deviation (DD), and corner radius (R_C). To overcome the inability of the Taguchi method to solve multi-response optimization problems, the Utility approach has been adopted to optimize all three responses simultaneously. This proposed hybrid multi-response optimization technique can be widely used for other conventional as well as non-conventional manufacturing processes to enhance the machining accuracy.

2 Methodology

2.1 Taguchi's design of experiment

The Taguchi-based methodology uses orthogonal arrays to organize the cutting parameters with their levels that affect the machining process. The response variables are categorized into three groups, i.e. smaller the better, larger the better, and nominal the best. In the Taguchi method, signal-to-noise (S/N) is used as a measure of quality characteristics which indicates the deviation from the desired value. The S/N ratio value for different types of response variables is determined by using the following formulae, i.e.

a) Smaller the better,

$$ {}^S\!/_N \text{ ratio} = -10 \log \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \tag{1} $$

b) Larger the better,

$$ {}^S\!/_N \text{ ratio} = -10 \log \frac{1}{n} \sum_{i=1}^{n} y_i^2. \tag{2} $$

2.2 The utility concept

The performance of any product or machining process is evaluated based on different quality characteristics. These quality characteristics are combined to produce a composite index that represents the overall utility of the process. This overall utility is the sum of utilities of each quality characteristic.

According to the utility theory [2,3] if x_i is the measure of the effectiveness of ith quality characteristic and there are n characteristics evaluating the performance, then the joint utility function can be expressed as:

$$ U(x_1, x_2, \ldots, x_n) = f[U_1(x_1), U_2(x_2), \ldots, U_n(x_n)]. \tag{3} $$

It is assumed that the quality characteristics have no interactions between them. Hence the overall utility function becomes a linear sum of individual utilities as follows:

$$ U(x_1, x_2, \ldots, x_n) = \sum_{i=1}^{n} W_i U_i(x_i) \tag{4} $$

where $U_i(x_i)$ is the utility of the ith quality characteristic and W_i is the weight assigned to ith characteristic and the sum of weights for all characteristics is equal to 1.

Table 1. Chemical composition of D_2 tool steel.

Element	C	Mn	Si	Cr	Ni	P	S	Mo	V	Co	Cu	Fe
Weight percentage (%)	1.55	0.60	0.60	11.8	0.3	0.03	0.03	0.8	0.8	1	0.25	Balance

Table 2. Machining parameters and their levels.

Parameter	Unit	Symbol	Level		
			1	2	3
Pulse on time (T_{ON})	μs	A	105	110	115
Pulse off time (T_{OFF})	μs	B	30	40	50
Servo voltage (SV)	V	C	30	35	40
Wire feed rate (WF)	mm/min	D	4	6	8

Fig. 1. Experimental set up.

The preference number for each quality characteristic is expressed as follows:

$$P_i = A * \log\left(\frac{x_i}{x'_i}\right) \qquad (5)$$

where x_i is the value of any quality characteristic i, x'_i is the minimum acceptable value of quality characteristic i and A is a constant. The value of A can be determined by the condition that if $x_i = x^*$ (where x^* is the best or most accepted value of ith quality characteristic), then $Pi = 9$ so,

$$A = \frac{9}{\log\dfrac{x^*}{x'_i}}. \qquad (6)$$

The overall utility can then be calculated as follows:

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

3 Experimentation

In the present study, the experiments have been conducted on Elektra CNC wire electrical discharge machine as shown in Figure 1. A 0.25 mm diameter Zn coated Brass wire has been used as tool electrode and de-ionized water is used as dielectric fluid. AISI D_2 tool steel of 12 mm thickness has been used as workpiece material. The chemical composition of this material is given in Table 1.

Based on the detailed study of past research works, pulse on time (T_{ON}), pulse off time (T_{OFF}), servo voltage (SV), and wire feed rate (WF) were chosen as machining parameters. Each parameter is varied in three levels as given in Table 2 [19]. All other parameters were kept constant during the experiment. In the present research work, experiments have been planned as per Taguchi's L_9 orthogonal array to reduce the number of experiments and hence the experimental cost. If the traditional approach is followed considering four input parameters with three levels, then 3^4 numbers of experiments (i.e. 81 numbers of experiments) have to be performed to analyze the effect of input parameters on the machining performance. Nine experiments were conducted according to Taguchi's L_9 orthogonal array as shown in Table 3. These nine experimental results obtained following Taguchi's L_9 orthogonal array can also predict the same optimum machining performance which could be obtained by performing 81 numbers of experiments. Minitab software was used for Taguchi design.
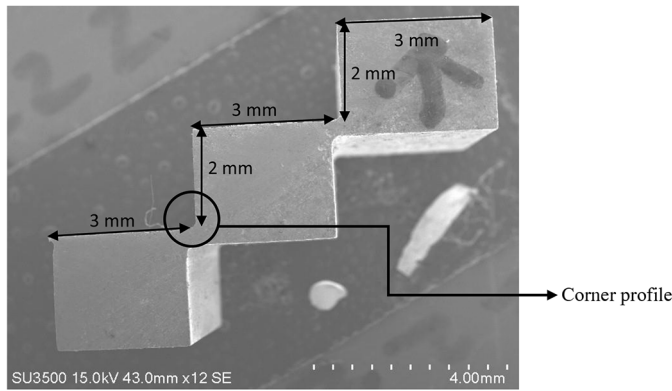
In each experiment, a step-cut of 13 mm was made to cut and the machining time for each experimental run was measured using a digital stopwatch (in minutes and seconds). Figure 2 shows the machining profile of the

Table 3. Taguchi's L$_9$ orthogonal array design.

Expt. no.	T_{ON}	T_{OFF}	SV	WF
1	105	30	30	4
2	105	40	35	6
3	105	50	40	8
4	110	30	35	8
5	110	40	40	4
6	110	50	30	6
7	115	30	40	6
8	115	40	30	8
9	115	50	35	4

Table 4. Experimental results.

Sl. no.	V_C (mm/min)	DD (%)	R_C (mm)
1	1.13	0.23	0.11
2	0.56	8.23	0.13
3	0.29	1.15	0.14
4	1.24	2.54	0.20
5	0.81	6.23	0.18
6	0.63	7.62	0.19
7	1.62	4.85	0.17
8	1.59	2.31	0.16
9	0.84	7.31	0.13

Fig. 2. Machining profile of the workpiece.

Table 5. Utility value of responses.

Sl. no.	Individual utilities (U_i)			Overall utility index (U_o)
	V_C	DD	R_C	
1	7.1327	9	9.0000	8.3776
2	3.4427	0	6.4851	3.3093
3	0.0000	4.9474	5.3695	3.4390
4	7.6015	2.9620	0.0000	3.5212
5	5.3737	0.7010	1.5861	2.5536
6	4.0589	0.1957	0.7722	1.6756
7	9.0000	1.3338	2.4466	4.2601
8	8.9022	3.2020	3.3593	5.1545
9	5.5640	0.2995	6.4851	4.1162

workpiece. The cutting rate was calculated by using the formula;

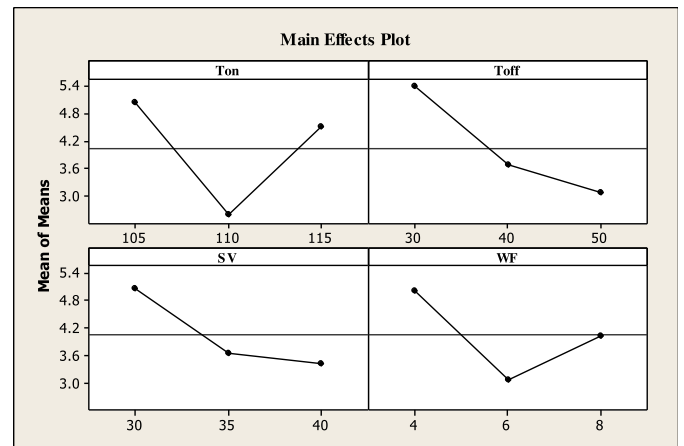$$V_C = \frac{L}{t}\,\mathrm{mm/min} \qquad (8)$$

where L is the machining length measured in mm using a scanning electron microscope (SEM) and t is the machining time in minutes. Corner radius (R_C) was also measured by using SEM analysis and the deviation of the measured dimension was calculated (in percentage) using the following expression:

Dimensional deviation (DD) = [|measured value − actual value| / actual value]*100.

Table 4 shows the experimental results for V_C, DD, and R_C.

4 Results and discussions

The experimental data given in Table 4 are analyzed using the utility concept [2,3] which is described in the earlier section. In this study, V_C is considered as a larger-the-better type response. Whereas, DD and R_C indicate smaller-the-better type responses. Utility values or preference number of each quality characteristic was calculated

Fig. 3. Effects of process parameters on overall utility index.

by using equation (5). Then the overall utility index was computed using equation (6) by considering the weights of each response variable as shown in Table 5.

To study the effect of process parameters such as T_{ON}, T_{OFF}, SV, and WF on the overall utility, a set of graphs is plotted as shown in Figure 3. In this figure, four different graphs are plotted.

Table 6. Results of ANOVA.

10	SS$_f$	DOF	SS$_m$	F	P (%)
A	10.0394	2	5.0197	2.0922	34.53
B	8.6251	2	4.3126	1.7974	29.66
C	4.7985	2	2.3993	1.0000	16.51
D	5.6113	2	2.8057	1.1694	19.3
Error	C	–	–	–	–
Total	29.0744	8	–	–	100

In the first graph, the nature of variation of overall utility values corresponding to low, medium, and high pulse on time is presented. It is observed that the mean value of overall utility is highest at the low value of pulse on time. It may be noted here that the low value and high value of pulse-on time are selected based on two factors. Frequent wire breakage occurred when the pulse on time was more than 120 μs and on the other hand, a very low value of pulse-on time resulted in a reduced cutting rate. At the low value of pulse on time (i.e. $T_{ON} = 105$ μs), the energy input is comparatively low, resulting in lower crater size and hence better dimensional accuracy and corner radius. Since the difference between low and high value of pulse on time is not appreciable the cutting rate is not decreased much. As a result of which two output parameters have been improved with little less in cutting rate.

In the same way, the second graph represents the variation of overall utility with different values of pulse off time. It is observed from this graph that corresponding to low value of pulse off time, the overall utility value is very high. With a low value of pulse off time, there is more number of discharges in a given time resulting in more amount of material removal and hence cutting rate. Similarly, the third graph represents the variation of overall utility with different values of servo voltages. Since servo voltage has a greater effect on dimensional deviation and corner radius, therefore low value of servo voltage is favoring for better dimensional accuracy and corner radius.

Similarly, the fourth graph represents the variation of overall utility at different values of wire feed rate. Corresponding to low value of wire feed rate (i.e. 4 mm/min) the overall utility is high. When the feed rate is low, the cutting velocity is very high due to more energy input into the workpiece. This does not have much effect on dimensional deviation and corner radius. As a result of which the overall utility would be higher. Hence, from this experimental analysis, it is found that the best combination of the input parameters is $A_1B_1C_1D_1$ i.e. 105 μs pulse on time, 30 μs pulse off time, 30 V servo voltage, and 4 mm/min wire feed rate.

Then, analysis of variance (ANOVA) was carried out to find out the significant effect of each process parameter on the overall utility index in terms of F-ratio as shown in Table 6. A higher value of F-ratio indicates that the respective cutting parameter is having a great influence on the overall machining performance [19]. From the results, pulse on time is found to be the most influencing factor with the highest percentage contribution (i.e. 34.53%) towards the overall utility index, followed by pulse off time (29.66%), wire feed rate (19.30%), and servo voltage (16.51%).

5 Conclusions

From the present experimental study the following conclusions are obtained:
– Taguchi-based utility approach is a very simple and robust optimization tool to obtain the best combination of input parameters for optimum overall performance in any machining process.
– The optimum process parameters setting for this Wire EDM case study that lead to maximum cutting rate and minimum dimensional deviation and corner radius are the first level of pulse on time (i.e. 105 μs), the first level of pulse off time (i.e. 30 μs), the first level of servo voltage (i.e. 30 V) and the first level of wire feed rate (i.e. 4 mm/min) which means the first experimental set of L$_9$ orthogonal array gives the best result.
– From the ANOVA analysis, pulse on time is found to have a maximum impact (34.53%) on the overall performance.
– Further, surface texture, recast layer thickness and heat-affected zone can be studied.

6 Implications and influences

This proposed methodology will be extremely helpful in fulfilling the techno-economic aspects of the WEDM process as well as other conventional and non-conventional manufacturing processes. This paper will be of interest to readers in the areas of production engineering.

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