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ORIGINAL ARTICLE

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Multi response optimization of wire EDM operations using robust design of experiments

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Abstract In this present study a multi response optimization method using Taguchi's robust design approach is proposed for wire electrical discharge machining (WEDM) operations. Experimentation was planned as per Taguchi's L16 orthogonal array. Each experiment has been performed under different cutting conditions of pulse on time, wire tension, delay time, wire feed speed, and ignition current intensity. Three responses namely material removal rate, surface roughness, and wire wear ratio have been considered for each experiment. The machining parameters are optimized with the multi response characteristics of the material removal rate, surface roughness, and wire wear ratio. Multi response S/N (MRSN) ratio was applied to measure the performance characteristics deviating from the actual value. Analysis of variance (ANOVA) is employed to identify the level of importance of the machining parameters on the multiple performance characteristics considered. Finally experimental confirmation was carried out to identify the effectiveness of this proposed method. A good improvement was obtained.

Keywords ANOVA · MRR · MRSN · Surface roughness · WEDM · WWR

1 Introduction

The wire electro discharge machining (WEDM) process contributes a predominant role in some manufacturing sectors recently; since this process has the capacity to cut complex and intricate shapes of components in all electrically conductive materials with better precision and accuracy. In the WEDM process there is no relative contact between the tool and work material, therefore the work material hardness is not a limiting factor for machining materials by this process. In this operation the material removal occurs from any electrically conductive material by the initiation of rapid and repetitive spark discharges between the gap of the work and tool electrode connected in an electrical circuit [1–3] and the liquid dielectric medium is continuously supplied to deliver the eroded particles and to provide the cooling effect. A small diameter wire ranging from 0.05 to 0.25 mm is applied as the tool electrode [4]. The wire is continuously supplied from the supply spool through the work-piece, which is clamped on the table by the wire traction rollers. A gap of 0.025 to 0.05 mm is maintained constantly between the wire and work-piece [5]. Deionized water of 15 micro semen/cm is applied as the dielectric fluid [3]. A collection tank that is located at the bottom is used to collect the used wire and then discard it. The wires once used cannot be reused again due to the variation in dimensional accuracy [6]. The dielectric fluid is continuously flashed through the gap along the wire, to the sparking area to remove the byproducts formed during the erosion [7]. Brass, aluminum and zinc coated brass or copper wires are widely applied as the tool electrode. Nowadays WEDM is an important machine tool to produce complex and intricate shapes of components in areas such as tool and die making industries, automobile, aerospace, nuclear, computer, and electronics industries.

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2 Literature review

Since WEDM is an essential operation in several manufacturing processes in some industries, which need variety, precision and accuracy are of great important. In order to improve the performance namely the surface roughness, cutting speed, dimensional accuracy, and material removal rate of the WEDM process several researchers have attempted previously. However, the full potential utilization of this process is not completely solved because of its complex and stochastic nature and the increased number of variables involved in this operation [2, 6].

The various technological and NC aspects of the WEDM process were analyzed by [8]. Kinoshita et al. [9] pointed out that the ratio between the equilibrium clearance and the amplitude of wire vibration is the most appropriate value to judge the short circuit gap. A number of authors have performed research related to wire rupture problems. To avoid short sparks which causes the wire to rupture, Tanimura et al. [10] developed a short circuit detecting system, which is performed by adjusting the chock inductance of the pulse generator. They reported that the unusual high rate of short circuit pulses during a period of 30 ms or more proceeds wire rupture. Kinoshita et al. [11] analyzed the various types of wire breaking. To prevent the wire breaking they developed a control system by means of monitoring the pulse frequency. Once a sudden rise of pulse frequency was detected, the pulse generator and servo system was turned off instantaneously to prevent the wire rupture from breaking. However, the machining efficiency was much reduced by such control strategy and the system was good if the work-piece thickness is restricted to 20 mm.

Scott et al. [6] constructed a mathematical model to predict the material removal rate and surface finish when machining D2 tool steel material at different machining conditions. They found that there is no single combination of levels of the different factors that can be optimal under all circumstances. To find the optimal machining parameters the non-dominated point approach was applied, using explicit enumeration of all possible combinations and the dynamic programming method. Dauw et al. [7] developed a mathematical model to analyze the wire deflection during machining. The deviation of the wire position relative to the programmed wire path position was continuously measured and corrections were made during machining of complex shapes, arc, and contours. In this study, substantial gain of machining time and improvement in corners' accuracy was obtained. Tarng et al. [12] formulated a neural network model and simulated annealing algorithm in order to predict and optimize the surface roughness and cutting velocity of the WEDM process when machining SUS–304 stainless steel materials.

Spedding et al. [2] attempted to model the WEDM process through the response surface methodology and artificial neural networks and found that the model accuracy of both was better. The same authors [5] attempted further to optimize the surface roughness, surface waviness, and speed of the artificial neural networks predicted values using a constrained optimization model. Huse et al. [13] developed a model to estimate the MRR in corner cutting of the WEDM by considering wire deflection in terms of discharge angle. Lin [14] et al. proposed a control strategy based on Fuzzy logic to improve the machining accuracy at corner parts of the WEDM process. Jun Qu et al. [15] derived a mathematical model for the material removal rate of a cylindrical wire EDM process. The same authors [16] investigated through a mathematical model the surface integrity and roundness of cylindrical WEDM parts using brass and carbide work material. They found through the model a good estimate of the surface finish and roundness of cylindrical WEDM parts.

Gokler et al. [17] investigated under various experimental conditions the surface roughness achievable for 1040, 2379, and 2738 steel materials and the relative machining parameters for the WEDM process. Puri et al. [18] investigated the variation of geometrical inaccuracy caused due to wire lag with various machine control parameters. In order to predict the performance characteristics of the WEDM process Ramakrishnan et al. [19] developed a mathematical model using the response surface methodology. A good amount of research has already been done in the area of WEDM technology. To the best of the knowledge of the authors of this work, there is not found any published paper for optimizing multiple performance characteristics of the WEDM process using the Taguchi method. Keeping this consideration in view, this paper describes optimization of multiple performance characteristics using the robust parametric design approach, for achieving a better material removal rate, surface finish, and wire wear ratio.

3 Methodology

Taguchi's robust design is a simple, systematic and more efficient method to determine optimum or near optimum settings of design parameters [20]. Many researchers have attempted to analyze and optimize a single performance characteristic of a manufacturing process using Taguchi methodology [5, 18, 20, 21]. However, optimization of multiple performance characteristics was rarely discussed in literature [22]. In this present work, optimization of WEDM operations using Taguchi's robust design methodology with multiple performance characteristics is proposed. In order to optimize the multiple performance characteristics, Taguchi parametric design approach was not applied directly. Since each performance characteristic may not have the same measurement unit and of the same category in the S/N ratio analysis. Therefore to solve problems of this kind, steps 1–3 followed first then the traditional Taguchi technique for single response optimization has performed.

Step 1 Normalize the loss function corresponding to each performance characteristics as follows:

$$S_{ij}{=}L_{ij}/\overline{L_i} \tag{1}$$

where S_{ij} is the normalized loss function for the ith performance characteristic in the jth experiment, L_{ij} is the loss function for the ith performance characteristic in the jth experiment and $\overline{L_i}$ is the average loss function for the ith performance characteristic.

Step 2 Apply a weighting method to determine the importance of each normalized loss function. The total loss function TL_j in the jth experiment as given under:

$$TL_j = \sum_{i=1}^{m} w_i S_{ij} \tag{2}$$

where W_i is the weighting factor for the ith performance characteristic and m is the number of performance characteristics.

Step 3 Transform the total loss function into a multi response S/N ratio (MRSN) as follows:

$$MRSN = -10\log(TL_j)\,. \tag{3}$$

Based on multi response S/N ratio (MRSN) the optimal factors or level combination are determined like the traditional Taguchi technique. Finally the optimal process parameters are verified through the confirmation experiment. Based on the type of performance characteristics, Taguchi categorized performance characteristics into three different kinds, such as; the nominal the better, the smaller the better, and the larger the better. In this study the smaller the better, and larger the better principles are considered to minimize the surface roughness and wire wear ratio and maximize the material removal rate respectively. For that case, the corresponding loss function can be expressed as follows:
For the smaller the better

$$L_{ij} = 1/n * \sum_{k=1}^{n} y_{ijk}^2 \tag{4}$$

For the larger the better

$$L_{ij} = 1/n * \sum_{k=1}^{n} 1/y_{ijk}^2 \tag{5}$$

where, n represents the number of repeated experiments and L_{ij} is the loss function of the ith performance characteristic in the jth experiment and y_{ijk} is the experimental value of the ith performance characteristic in the jth experiment at the kth test.
The next step to be performed after the statistical analysis of the MRSN ratio is an analysis of variance (ANOVA). ANOVA is used to determine the significance of each selected machining parameter of the experimentation.

4 Experimental details

4.1 Material, machine tool, and measurement

Heat treated tool steel is used as the work material for experimentation. The experiment was planned according to Taguchi's L16 orthogonal array. To perform the experiment a five-axis Robofil 290P CNC WEDM machine manufactured by Charmilles Technologies, Switzerland was applied. A 0.25 mm diameter zinc coated brass wire was selected as the tool electrode for experimentation. At each experiment a 14 mm width of work material was made to cut. The work specimen height was selected as 20 mm. The chemical composition of the work specimen is shown in Table 1.

Table 1. Chemical composition of tool steel (heat treated)

C	Mn	Cr	W	V	Si	Fe
0.95	1	0.5	0.5	0.10	0.2	Balance

The mean cutting speed data (Cs) was observed directly from the computer monitor, which was attached to the machine tool. Generally, during this process the wire diameter is kept constant. Therefore, the width of cut (W) remains constant. Therefore, the MRR for the WEDM operation is calculated using Eq. 6 which is shown below:

$$\text{MRR} = Cs \times L \tag{6}$$

where Cs = cutting speed in mm/mint. L = thickness of the material in mm. A Talysurf at 0.8 mm cut-off value was applied to measure the surface roughness (Ra) of each specimen.

Wire wear ratio (WWR) is defined as the loss of wire after machining divided by the initial wire weight. The WWR was calculated using the following:

$$\text{WWR} = \text{WWL}/\text{IWW} \tag{7}$$

where WWL is the loss of wire weight and IWW is the initial wire weight. To measure the weight an electronic balance with 0.001 gm accuracy was applied. In order to minimize the measurement error the average value of four-weight measurements were used.

4.2 Selection of cutting parameters

The variables that affect the performance of the WEDM process are identified based on experience, discussion made with the expert, survey of literature [2,18,19,22] and preliminary experimentation performed by the author by considering more number of variables. Through the above observation, five machining parameters, which are vigorously affects the material removal rate; surface roughness and wire wear ratio was selected. Those are shown in Table 2.

Table 2. Machining parameter ranges and their levels

Sl.no.	Parameter	Unit	Symbol	Range		Level			
				Actual	Decided	1	2	3	4
1	Pulse on time	µsec	A	0–2	0.6–1.2	0.6	0.8	1	1.2
2	Wire tension	Kg	B	0–2	1–1.6	1	1.2	1.4	1.6
3	Delay time	µsec	C	1–16	4–10	4	6	8	10
4	Wire feed speed	m/min	D	1–14	8–14	8	10	12	14
5	Ignition current intensity	Ampere	E	2–33	6–12	6	8	10	12

Table 3. Layout of L16 orthogonal array for experimentation

Experiment number	A	B	C	D	E
1	1	1	1	1	1
2	1	2	2	2	2
3	1	3	3	3	3
4	1	4	4	4	4
5	2	1	2	3	4
6	2	2	1	4	3
7	2	3	4	1	2
8	2	4	3	2	1
9	3	1	3	4	2
10	3	2	4	3	1
11	3	3	1	2	4
12	3	4	2	1	3
13	4	1	4	2	3
14	4	2	3	1	4
15	4	3	2	4	1
16	4	4	1	3	2

Table 4. Results of material removal rate (mm^2 /min) surface roughness and wire wear ratio

Exp. number	Material removal rate (mm^2/min)				Surface roughness (micron)				Wire wear ratio
	trial-1	trial-2	trial-3	trial-4	trial-1	trial-2	trial-3	trial-4	
1	37	40	38	41	3.71	3.85	3.73	3.99	0.06
2	50	48	44	47	2.96	2.98	3.02	2.93	0.069
3	49	47	54	50	2.33	2.37	2.52	2.41	0.065
4	61.5	62	51	54	2.19	2.21	2.17	2.03	0.078
5	60	61	65	66	3.15	3.21	3.18	3.24	0.087
6	61	69	73	75	2.85	2.78	2.83	3.24	0.09
7	42	39	43	38	2.92	2.97	2.89	2.91	0.045
8	58	53	54	57	2.72	2.78	2.86	2.88	0.062
9	48	54	49	55	3.05	2.82	2.89	2.83	0.077
10	55	52	51	54	3.11	3.15	3.18	3.24	0.067
11	89	85	87	93	3.42	3.37	3.44	3.23	0.08
12	62	64	63	64	3.36	3.41	3.52	3.39	0.07
13	52	55	58	53	2.83	3.07	3.12	3.13	0.079
14	78	74	70	71	3.48	3.36	3.39	3.54	0.074
15	79	76	75	72	3.66	3.49	3.58	3.61	0.1
16	80	88	83	86	3.31	3.22	3.15	3.39	0.098

4.3 Parameter level and orthogonal arrays

The degrees of freedom for each parameter were selected as four. Experiments were conducted well all over the ranges of each selected parameter. The machining ranges of parameters were identified from the manufacturer manual [3]. To obtain a reliable database each experiment was repeated at four times and the results were presented in Table 4.

5 Results and discussion

This section, discusses the experimental findings using the MRSN ratio and the analysis of the parametric influences on the performance characteristics. An analysis of variance (ANOVA) is applied to estimate the effect of various machining parameters on optimization of multiple performance characteristics of the WEDM process. Based on the results of the MRSN ratio and ANOVA results, optimal machining parameters with the consideration of multiple performance characteristics have been obtained and verified.

5.1 Analysis of the experimental data

The first step in data analysis of this present study is to summarize the test results for each experiment performed by the use of Taguchi's L16 orthogonal array. The MRSN ratio was calculated using different combinations of weighting factors for each response considered. Prior to calculating the MRSN ratio, the loss function for the performance characteristics has to be found first. The loss function for the material removal rate was calculated by applying Eq. 5. Similarly Eq. 4 was applied to calculate the loss function for surface roughness and the wire wear ratio. Equations 1–5 were utilized to calculate MRSN ratios with different combinations of the weighting factor and the results are presented in Table 5. For case 1, higher priority was given to material removal rate; therefore the weighting factor ($w_1 = 5$) was chosen for the material removal rate. Similarly for the other performance characteristics namely the surface roughness ($w_2 = 3$), and wire wear ratio ($w_3 = 2$) were selected. However, for case 2, higher priority was given to minimize surface roughness, therefore the weighting factor for surface roughness ($w_2 = 5$) was chosen for this case. The weighting factors for the remaining performance characteristics namely the material removal rate (weighting factor $w_1 = 3$) and wire wear ratio (weighting factor $w_3 = 2$) were selected.

To calculate the MRSN ratio at different combinations of weighting factor a computer program was developed using a C++ programming language. The mean MRSN ratio at each parameter level is calculated. Since the experimental design is orthogonal, it is possible to separate out the effect of each ma-

Table 5. Multi-response S/N ratio with different weighting factor

Experiment number	Multi-response S/N ratio (dB) case-1 $w_1 = 5$, $w_2 = 3$, $w_3 = 2$	Multi-response S/N ratio (dB) case-2 $w_1 = 3$, $w_2 = 5$, $w_3 = 2$
1	−11.2075	−11.2695
2	−10.7384	−10.3249
3	−9.9584	−9.2942
4	−9.3457	−8.7929
5	−10.0095	−10.225
6	−8.5188	−8.1927
7	−11.2985	−8.1927
8	−9.6411	−9.4169
9	−10.3889	−10.1031
10	−10.2682	−10.1031
11	−8.091	−9.7756
12	−9.8024	−10.1677
13	−10.2738	−10.001
14	−9.4179	−10.0173
15	−12.8188	−12.3616
16	−10.4608	−10.1633

chining parameter at different factor levels. The calculated mean MRSN ratio of each machining parameter at different factor levels is presented in Tables 6 and 7 for case 1 and case 2, respectively. In addition, for the above two cases the grand mean of the MRSN ratio for all the 16 experiments were calculated and the results are shown in Tables 6 and 7, respectively.

5.2 Analysis of variance

After the MRSN and mean MRSN ratio calculation for each experiment of case 1 and case 2, the next step in the data analysis is to estimate the effect of each machining parameter on the responses and to perform the analysis of variance (ANOVA).

ANOVA is accomplished by separating the total variability of the MRSN ratio, which is measured by the sum of the squared deviations from the total mean of the MRSN ratio, into contributions by each of the machining parameters and the error. First the total sum of the squared deviation (SS_t) from the grand mean of the MRSN ratio (η_m) can be calculated as

$$SS_t = \sum_{j=1}^{p} (\eta_j - \eta_m)^2 \tag{8}$$

where p is the number of experiments in the orthogonal array and η_m is the grand mean of the MRSN ratio and η_j is the mean MRSN ratio for the jth experiment.

The total sum of squared deviation (SS_t) can be decomposed into two components; the sum of squared deviations due to each process parameter (SS_d) and the sum of the squared errors (SS_e). The percentage contribution (ϱ) is the ratio of SS_d to SS_t. In order to identify the significant effect of each process parameter on the performance characteristics, the F – test, which is the ratio of the mean of the squared deviation (SS_m) to the mean of the squared error (SS_{em}) is calculated. Where SS_m is equal to the sum of the squared deviation (SS_d) divided by the number of degrees of freedom associated with the process parameter. The larger the F value, the greater the effect on the performance character due to the change of the parameter.

The results of ANOVA for case 1 of MRSN are shown in Table 8. In which the percentage contribution for all factors affecting the multiple performance characteristics appear. The factors effect on MRSN for case 1 is also represented graphically in Fig. 1 which makes it easy to visualize the relative contributions of the various factors on the machining characteristics. Comparing the ANOVA results and percentage contribution for each factor it was found that the pulse on time is the most influential factor. Since this has the highest F value (6.978) and percentage contribution (46.4077%). Ignition current intensity and delay time are found as statistically significant factors for the multi response optimization of case 1. The parameter which the percentage contribution falls less than 10% is considered statistically insignificant. In this case wire feed speed is considered insignificant and it is included in the error term. Hence this has the smallest F value and percentage contribution (6.551%). With an increase of pulse on time up to level three (A3) and ignition current intensity at level four (E4), the response shows an increasing trend. Since more priority is given to material removal rate than surface roughness and wire wear ratio. However, increase of pulse on time beyond level three increases the work-piece surface roughness and wire wear ratio owing to greater energy of discharges. Increases of wire tension at the rate of high discharge energy causes more wire breakage. Hence C1 is better. Through the above investigation the optimal machining parameters identified for case 1 of multi response optimization are A3B2C1E4.

Table 6. Mean multi-response S/N ratio table for weighting factor $w_1 = 5$, $w_2 = 3$, $w_3 = 2$

Machining parameter	Symbol	Mean multi-response S/N ratio (dB)				
		Level-1	Level-2	Level-3	Level-4	Max-Min
Pulse on time	A	−10.992	−9.7	−9.6378	−10.413	1.7679
Wire tension	B	−10.470	−9.7348	−10.54	−9.813	0.806
Delay time	C	−9.5695	−10.722	−9.8516	−10.2966	1.1727
Wire feed speed	D	−10.4316	−9.686	−10.174	−10.2681	0.5821
Ignition current intensity	E	−10.8576	−10.376	−9.726	−9.6386	1.219

Total mean multi-response S/N ratio = −10.140 dB

Table 7. Mean multi-response S/N ratio table for weighting factor $w_1 = 3$, $w_2 = 5$, $w_3 = 2$

Machining parameter	Symbol	Mean multi-response S/N ratio (dB)				
		Level-1	Level-2	Level-3	Level-4	Max-Min
Pulse on time	A	−9.9065	−9.5895	−10.0374	−10.6782	1.0887
Wire tension	B	−10.4413	−9.6457	−10.4894	−9.6352	0.8542
Delay time	C	−9.8503	−10.7567	−9.7079	−9.8967	1.0488
Wire feed speed	D	−10.4943	−9.9074	−9.9464	−9.8633	0.631
Ignition current intensity	E	−10.7885	−10.2648	−9.4556	−9.7027	1.3329

Total mean multi-response S/N ratio = −10.0529 dB

Table 8. Results of ANOVA for weighting factor $w_1 = 5$, $w_2 = 3$, $w_3 = 2$

Sources of variance	Sum of square	Degrees of freedom	Mean square	F value	Percentage contribution
A	8.6225	3	2.8742	6.978	46.4077
B	2.1513	3	0.7171	1.741	11.5786
C	2.8777	3	0.9592	2.029	15.488
E	3.6927	3	2.8742	2.989	19.875
Error (D)	1.2357	3	0.4119		6.551
Total	18.5799	15			100

Table 9. Results of ANOVA for weighting factor $w_1 = 3$, $w_2 = 5$, $w_3 = 2$

Sources of variance	Sum of square	Degrees of freedom	Mean square	F value	Percentage contribution
A	2.434	3	0.811	2.534	18.94
B	2.645	3	0.882	2.756	20.58
C	2.626	3	0.875	2.734	20.43
E	4.188	3	1.396	4.363	32.58
Error (D)	0.96	3	0.32	1	7.47
Total	12.853	15			100

Figure 2 represent the factor effects and Table 9 shows the results of ANOVA for case 2. With the results of ANOVA, ignition current intensity is identified as the most significant parameter; since it has the F value of 4.363 and percentage contribution of 32.58%. The pulse on time and delay time are considered as significant factor. The significant level of ignition current intensity and pulse on time are identified as E3 and A2, respectively. Since higher priority was given to minimize the surface roughness. Therefore the significant factor level has decreased from case 1 to case 2. However the delay time is increased considerably, which induces more uniform and stable spark, which is necessary to reduce the surface roughness and wire wear ratio. Increased wire tension at a low energy rate will reduce the wire vibration from its actual position. Therefore the significant level is increased to level three (C3). Again the wire feed speed is considered statistically insignificant, because it has a very low F value and percentage contribution (7.47%). Therefore this is included in the error term. Based on the above results the optimal cutting conditions obtained for case 2 are A2B4C3E3.

5.3 Verification of the experiments

The final step of the Taguchi's parameter design after selecting the optimal parameter is to predict and verify the improvement of the performance characteristics with the selected optimum parameters. The predicted optimum values of the SN ratio (η_{opt})

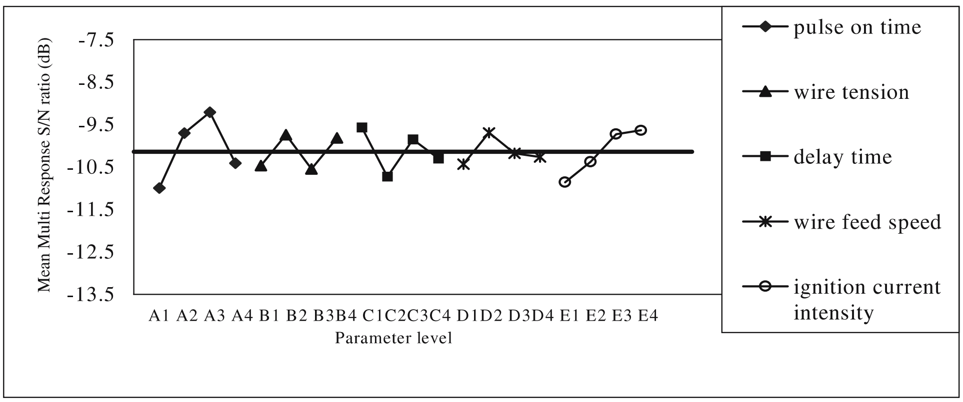


Fig. 1. Multi-response S/N ratio graph for weighting factor $w_1 = 5$, $w_2 = 3$, $w_3 = 2$

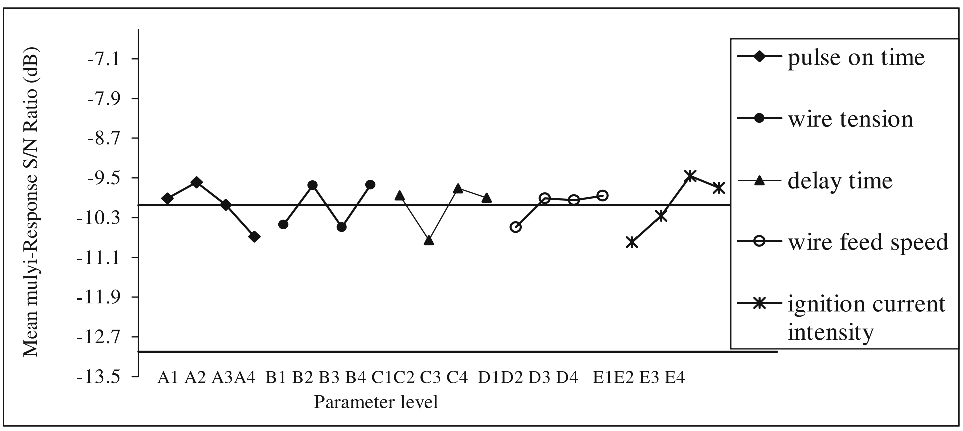


Fig. 2. Multi-response S/N ratio graph for weighting factor $w_1 = 3$, $w_2 = 5$, $w_3 = 2$

Table 10. Results of experimental confirmation for weighting factor $w_1 = 5$, $w_2 = 3$, $w_3 = 2$

	Initial cutting parameters	Optimal cutting parameters Prediction	Experiment
Level	A2B2C2D2E2	A3B2C1E4	A3B2C1E4
Material removal rate (mm^2/min)	64		94
Surface roughness (micron)	2.98		2.46
Wire wear ratio	0.076		0.061
S/N ratio (dB)	−11.017	−7.961	−8.5

Improvement in MRSN ratio= 2.517 dB

Table 11. Improvement of individual S/N ratio for weighting factor $w_1 = 5$, $w_2 = 3$, $w_3 = 2$

	Material removal rate (mm^2/min)	Surface roughness (μm)	Wire wear ratio
Initial cutting parameters (A2B2C2D2E2)	36.12	−9.48	22.38
Optimal cutting parameters (A3B2C1E4)	39.46	−7.82	24.29
Improvement in S/N ratio	3.34	1.66	1.91

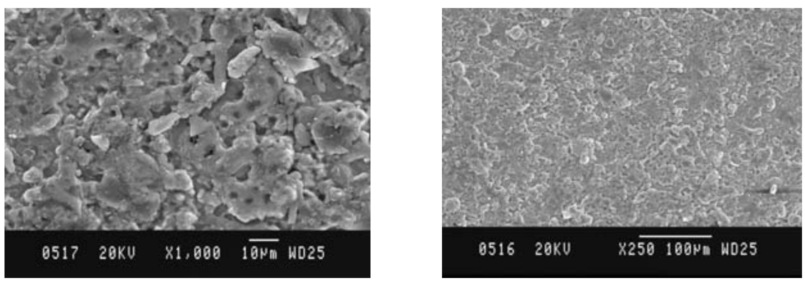
using the optimal level of process parameters can be calculated as

$$\eta_{opt} = \eta_m + \sum_{i=1}^{q} (\overline{\eta_i} - \eta_m) \tag{9}$$

where η_m is the grand mean of MRSN ratio, $\overline{\eta_i}$ is the mean MRSN ratio at the optimum level, and q is the number of main design parameters that significantly affect the multi performance characteristics.

Verification of the test results at the selected optimum conditions for case 1 is shown in Table 10. The predicted machining performance was compared with the actual machining performance and a good agreement was obtained between these performances. The improvement of the MRSN from the initial cutting parameters to optimal cutting parameter is 4.77 dB. Table 11 shows the improvement of the S/N ratio for the individual responses. Based on the experimental confirmation the material removal rate is increased 1.469 times. The surface roughness is decreased by 1.211 times, and the wire wear ratio is decreased by 1.246 times. Hence the machining performance for case 1 is improved significantly at the optimal conditions. Figure 3 shows scanning electron microscope (SEM) results of the verification experiments.

Table 12 shows the results of the confirmation experiment at the selected optimum machining parameters for case 2. A fine agreement was obtained between the predicted and the actual machining performance. The improvement of the S/N ratio for the individual responses is shown in Table 13. The material removal rate is increased 1.25 times. The surface roughness is decreased by 1.26 times, and the wire wear ratio is decreased by 1.13 times. This indicates improvement of the machining performance for case 2. The experimental results confirm the effectiveness of



a) b)

Fig. 3. SEM macrograph of the specimen machined at optimal parameter level (A3B2C1E4)

Table 12. Results of experimental confirmation for weighting factor $w_1 = 3$, $w_2 = 5$, $w_3 = 2$

	Initial cutting parameters	Optimal cutting parameters Prediction	Experiment
Level	A2B2C2D2E2	A2B4C3E3	A2B4C3E3
Material removal rate (mm^2/min)	64		80
Surface roughness (micron)	2.98		2.36
Wire wear ratio	0.076		0.067
S/N ratio (dB)	−10.836	−8.272	−9.02
Improvement in MRSN ratio 1.816 dB			

Table 13. Improvement of the individual S/N ratio for weighting factor $w_1 = 3$, $w_2 = 5$, $w_3 = 2$

	Material removal rate (mm^2/min)	Surface roughness (μm)	Wire wear ratio
Initial cutting parameters (A2B2C2D2E2)	36.124	−9.484	22.384
Optimal cutting parameters (A2B4C3E3)	38.062	−7.458	23.35
Improvement in S/N ratio(dB)	1.938	2.026	1.095

Taguchi's robust design for optimal machining parameters with multi response characteristics of WEDM operations.

6 Conclusion

This paper described the multi objective optimization of the WEDM process using parametric design of Taguchi methodology. It was observed that the Taguchi's parameter design is a simple, systematic, reliable, and more efficient tool for optimization of the machining parameters. The effect of various machining parameter such as pulse on time, wire tension, delay time, wire feed speed, and ignition current intensity has been studied though machining of heat-treated tool steel. It was identified that the pulse on time and ignition current intensity have influenced more than the other parameters considered in this study. Moreover the multiple performance characteristics such as material removal rate, surface roughness, and wire wear ratio for the WEDM process can be improved concurrently. The validity of the developed optimization tool was tested and provides a consistent result. Therefore a very beneficial multi objective optimization tool for manufacturing system especially for WEDM operations has been proposed in this paper. From the present analysis it is evident that the optimal parametric combination will be very beneficial to the manufacturing communities who are working in the WEDM process. Further research might attempt to consider the other performance criteria, such as surface waviness, form accuracy, and surface flatness as output parameters. The technique presented in this study might also be tried for the other non-traditional machining processes such as electro chemical machining, electron beam machining, laser beam machining, and water jet machining operations for effective utilization of such machine tools. This technique can also be applied for the various conventional machining operations to improve the performance characteristics simultaneously.

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