Optimization of process parameters for the machining of high carbon martensitic stainless steel using wire EDM

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ABSTRACT

KEYWORDS

Wire Electrical Discharge Machining (WEDM),
Taguchi Technique,
Design of Experiments (DOE),
Grey Relational Analysis (GRA),
Fuzzy logic,
Material Removal Rate (MRR).

Wire Electro Discharge Machining (WEDM) process parameters need to be optimized when new material is invented or even if some process variables changed Optimization of the WEDM process for machining of AISI 440C stainless steel using brass wire electrode was studied in this paper. In this work, based on Taguchi's (DOE), an orthogonal array L-12 is developed and experiments are conducted with eleven factors each at two levels. The experimental data is recorded for obtaining the response values of MRR and Kerf width. Grey relational analysis is done along with Taguchi to find the optimum set of input process parameters. The prediction of output values can be done using the Fuzzy logic approach. At last, a confirmation test is done to evaluate the exactness of the values between experimental and predicted, found that the prediction accuracy for MRR is about 94.92% and for Kerf Width is about 82.5%.

1. Introduction

In manufacturing sectors like automobiles, general engineering, etc. WEDM machining is a prominent one. Amongst many unconventional machining procedures, WEDM is used for machining harder materials, and for innovative complex profile making. This process consists of intermittent heating and cooling processes. Machining time mainly affects the intensity of crack size formation and the quality of the workpiece surface formed. For improving the machining efficiency and for the development of precise making of complex profiles, there is a requirement for the prediction of optimal parametric combination sets. As the process itself consists of several parameters, it is difficult to obtain optimal parametric combinations for proper machining of hard materials. So, by using various approaches in the Design of experiments, Taguchi's robust design is applied to obtain optimum parametric combinations for selected single response characteristics. This method reduces the trial of experiments to be conducted. For solving the complex inter relationships among the multi-responses, grey system theory is useful to obtain grey relational grades which are used to evaluate the optimal parametric combination sets. As a result, the combination of both the Taguchi method and the Grey relational analysis is applied for multiple characteristics optimization.

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Fuzzy Logic: Usually, we have a grey area between big and small, hot and cold, tall and short. Assigning values for such uncertain areas is not an easy task. This method assigns values to those variables and solves problems related to them. It is introduced by Zadeh. Fuzzy Logic finds its applications in inference systems, process parameters optimization, and manufacturing systems. The four main steps in this Fuzzy inference system are

- Fuzzification
- Fuzzy IF-THEN rules
- Aggregation
- Defuzzification

In the concerned topic, the work material used is AISI 440C stainless steel and hard brass wire as the electrode is used for the machining process. According to the Design of Experiments, Taguchi's L-12 orthogonal array is considered. Then, Grey relational analysis is performed after the execution of Taguchi's single response optimization to obtain multi-objective optimization of desired output responses such as Material removal rate (MRR) and Kerf width by varying input process parameters like Pulse ON time, Pulse OFF time, input current, wire feed rate sensitivity, gap, wire tension, water pressure, job height, gap voltage, gap current. The input machining process parameters with their corresponding levels are indicated in the Table 1.

2. Literature Review

Jeevamalar and Ramabalan (2015) created a process for optimizing EDM parameters using the Taguchi design to maximize the Material Removal Rate, Tool wear, and Surface Roughness. By determining the optimal variables, the exactness of the predicted results to the calculated results was checked, found that the Taguchi technique can be useful for both optimization and prediction.

Table 1
Machining parameters and their levels.

Input parameters	Symbol	Unit	Level 1	Level 2
Pulse on time	T_{ON}	µs	105	110
Pulse off time	T_{OFF}	µs	40	45
Input current	I/P CUR	A	1	2
Wire feed rate	WFR	mm/ min	20	25
Sensitivity	S		9	10
Gap	G	µm	12	14
Wire tension	WT	Kg f	4	5
Water pressure	WP	Kg f/ cm^2	90	99
Job height	JH	mm	1	2
Gap voltage	GV	V	20	25
Gap current	GC	A	1	2

Mohammad et al. (2012) investigated the optimization of the EDM process in which the input process parameters taken were Pulse ON time, Duty factor, Discharge current by using L27 Taguchi's Orthogonal array. They found that the desired output response Surface Roughness was optimized at Pulse ON time of 10 microseconds, the Duty factor of 7, and discharge current of 6 amperes.

3. Experimental Setup

The work material used in this concerned topic was AISI 440C stainless steel using the Brass wire electrode. The input parameters were taken from either the open literature or the trial and error method of the values.

- *Machine set-up for before machining*

RATNAPARKHI WEDM machine is used for conducting this experiment. The wire was made vertical on the verticality block and the workpiece is mounted and clamped to the worktable. For setting the work-coordinate system, a reference point is selected thereby the programming can be done easily. The reference point is considered at the workpiece's ground edges. A machining program is made for cutting a square workpiece profile of 30.2 mm x 30.2 mm. So twelve square blocks are cut for twelve experimental runs. Precautions will be generally taken to reduce errors during the experiment.

Table 2
Design of experiments with L12 orthogonal array and the experimental results.

EXP NO	T ON	T OFF	I/P CUR	WFR	S	G	WT	WP	JH	GV	GC	T_M	MRR	KW
1	105	40	1	20	9	12	4	90	1	20	1	34	1730	0.53
2	105	40	1	20	9	14	5	99	2	25	2	31	1900	0.49
3	105	40	2	25	10	12	4	90	2	25	2	24	2400	0.64
4	105	45	1	25	10	12	5	99	1	20	2	23	2560	0.66
5	105	45	2	20	10	14	4	99	1	25	1	22	2670	0.34
6	105	45	2	25	9	14	5	90	2	20	1	26	2260	0.31
7	110	40	2	25	9	12	5	99	1	25	1	21	2800	0.33
8	110	40	2	20	10	14	5	90	1	20	2	25	2356	0.61
9	110	40	1	25	10	14	4	99	2	20	1	21	2800	0.14
10	110	45	2	20	9	12	4	99	2	20	2	18	3270	0.23
11	110	45	1	25	9	14	4	90	1	25	2	16	3680	0.40
12	110	45	1	20	10	12	5	90	2	25	1	14	4200	0.5

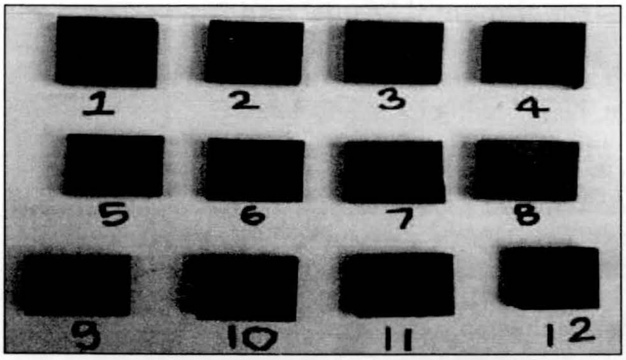

Fig. 1. Square blocks cut by WEDM.

4. Experimental Procedure on Wire EDM

The first step is clamping the workpiece to the WEDM machine. Then the wire is set vertical in position in the verticality block. By using Taguchi's L-12 orthogonal array, the workpiece is divided into 12 square blocks with each dimension 30.2*30.2*6 mm. Then machining is done according to the varying input parameters in twelve runs by considering the eleven input parameters at two levels. Machining time is noted for each experiment for the calculation of Material Removal Rate and Kerf Width. According to the concerned twelve experimental runs, the output responses are recorded in the respective Table 2 and the square-cutblocks obtained are shown in figure 1.

5. Calculation of Process Parameters

MRR is calculated by the division of the difference between the workpiece weight before machining and the workpiece weight after machining to the product of the density of the workpiece and machining time

$$\text{MRR} = \frac{W_{jb} - W_{ja}}{\rho t} \frac{mm^3}{\min} \quad \text{....................(1)}$$

Whereas,

W_{jb} = Initial weight of workpiece before machining in gm

W_{ja} = Final weight of workpiece after machining in gm

t = Machining time in minutes, ρ = Density of the material in gm/mm^3

Kerf width is measured in millimeters (mm). It is the measure of the amount of material that is wasted during machining and gives the dimensional accuracy of the finishing part. Kerf width is measured using digital Vernier calipers by taking the difference in width assumed and width obtained.

- *Grey system theory*

Calculation of signal to noise ratio: Taguchi's technique has three types of S/N Ratios. They are:

- The smaller the better
- The larger the better
- The nominal the better

The larger the better is chosen for the output response MRR, and the S/N ratio will be calculated from the formula 2 mentioned below.

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

Where n = number of replicas and y_{ij} = observed reaction value Where i = 1, 2... n; j = 1,2...k.

The smaller the better is chosen for the output response Kerf width and is calculated from the formula 3.

$$\text{S/N Ratio} = -\log_{10}\left(\frac{1}{n}\right)\sum_{i=1}^{n} y_{ij}^2 \quad \text{................(3)}$$

- *Fuzzy model development for the WEDM process*

The fuzzy model that has been designed for predicting MRR and Kerf Width for the WEDM operation uses eleven inputs and two outputs. In a fuzzy model, the selection of process parameters is the most important task. The shape of the membership function taken depends on the experimental results obtained for the selected input process parameters and the output response characteristics. For the input process parameters in this concerned topic the shape taken is triangular and the same for the output responses MRR and Kerf width. A Fuzzy model shows the complex interrelationships between the input and the output. The fuzzy inference system for MRR and Kerf width in terms of inputs is shown in the figure 2.

The membership function is a graphical representation of the experimental values obtained for the corresponding input variable and the output performance characteristic.

So, the membership functions for different input variables and the output process performance characteristics are shown in the figures below.

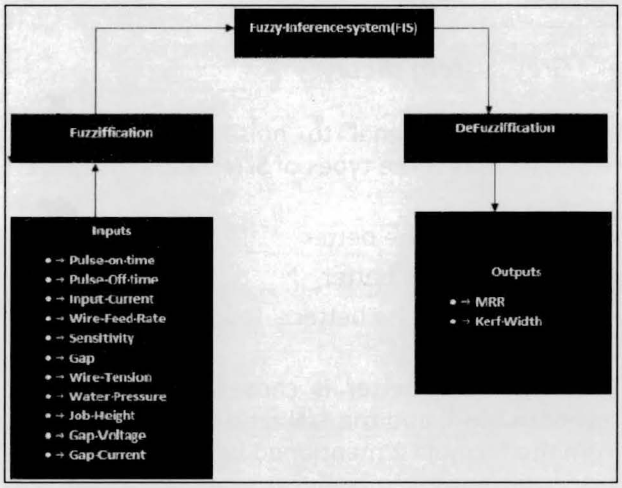

Fig. 2. Fuzzy Model for MRR and Kerf width for 440C Stainless steel

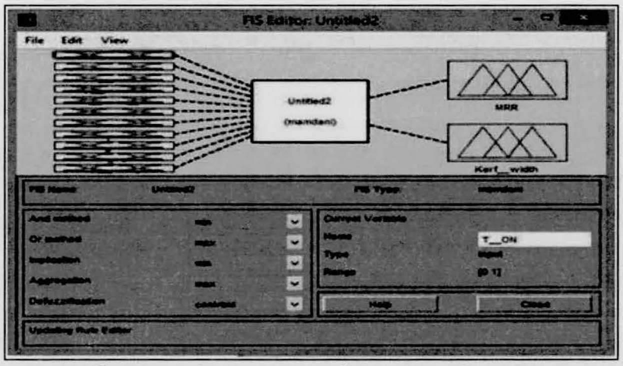

Fig. 3. Basic structure of Fuzzy Logic unit.

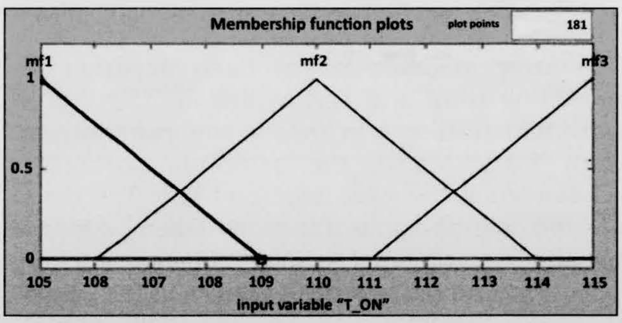

Fig. 4. Membership function for input variable.

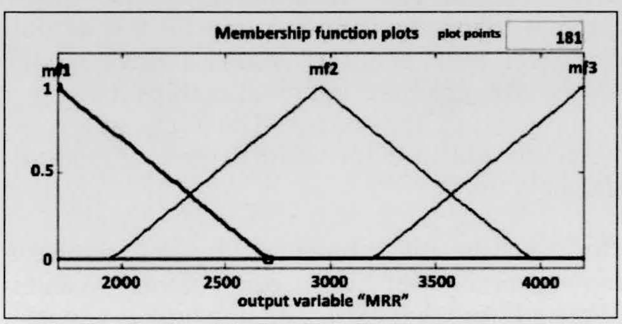

Fig. 5. Membership function for output response.

6. Experimental Results and Discussion

From the experiment, the results are summarized in the following Table 2 to Table 7.

Grey Relational Coefficients (GRC) are generally determined after the data pre-processing process. GRC is calculated with the help of the following formula and mentioned in the table 5.

The GRC $\Gamma\,(x_o\,(k\,),\,x_i\,(k\,))$ can be expressed by

$$\Gamma\big(x_o(k),x_i(k)\big)=\frac{\Delta_{\min}+\xi\Delta_{\max}}{\Delta_{0i}(k)+\xi\Delta_{\max}} \quad ....(4)$$

Finally, Grey relational analysis based on grey system theory is calculated and indicated in the table 6.

Based on Fuzzy Inference System, the defuzzification values of outputs are mentioned in the figure 7.

Based on MINITAB19 software, the Signal to noise ratio values for MRR are mentioned and the respective S/N ratio graphs are indicated in the figure 8.

Based on the graph obtained from the MINITAB19 software for the optimization of process parameters, individual optimal values are obtained at A2B2C1D2E2F1G1H1I2J2K1.

Table 3
Signal to noise ratio values for the experimental results.

Experiment Number	S/N Ratio MRR	S/N Ratio Kerf width
1	64.76092	5.514483
2	65.57507	6.196078
3	67.60422	3.876401
4	68.1648	3.609121
5	68.53023	9.370422
6	67.08217	10.17277
7	68.94316	9.629721
8	67.44351	4.293403
9	68.44316	17.07744
10	70.29096	12.76544
11	71.31696	7.9588
12	72.46499	6.2752

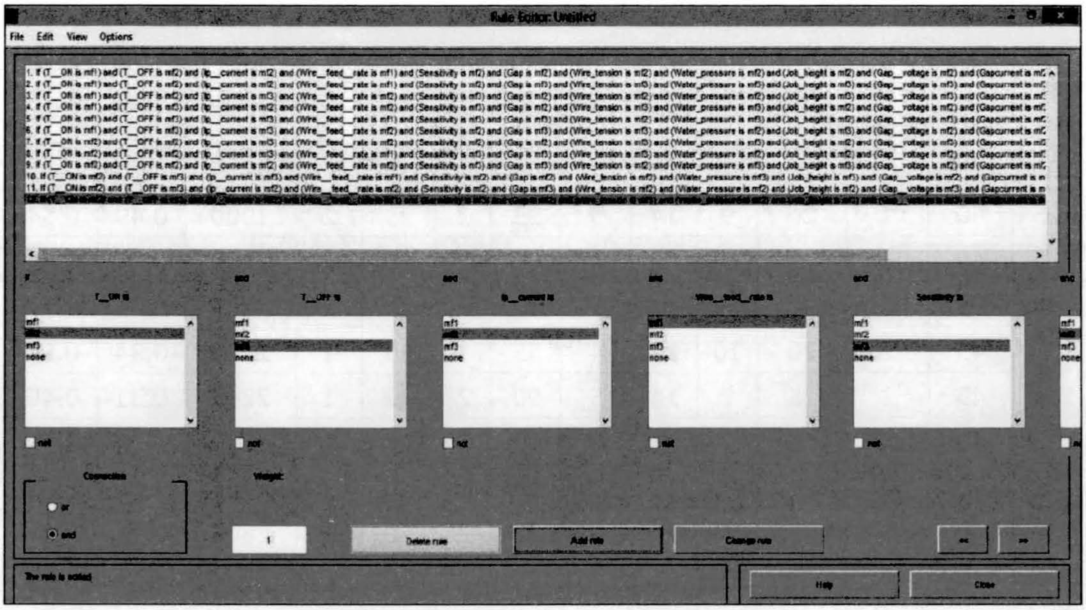

Fig. 6. Fuzzy rules in linguistic forms.

Table 4
Normalized S/N ratio values for the experimental results.

Experiment Number	N MRR	N KW
1	0	0.85853
2	0.105678	0.807923
3	0.369065	0.980155
4	0.441829	1
5	0.489262	0.572233
6	0.301302	0.51266
7	0.542861	0.552981
8	0.348204	0.949193
9	0.542861	0
10	0.717807	0.320158
11	0.850984	0.677044
12	1	0.794623

Table 5
Grey relational coefficients (GRC).

Experiment Number	GRC MRR	GRC KW
1	0.33	0.77
2	0.35	0.72
3	0.44	0.96
4	0.47	1
5	0.49	0.53
6	0.41	0.50
7	0.52	0.52
8	0.43	0.90
9	0.52	0.33
10	0.63	0.42
11	0.77	0.60
12	1	0.70

This corresponds to pulse on time at 110, pulse off time at 45, input current at 1, wire feed rate at 25, sensitivity at 10, the gap at 12, wire tension at 4, water pressure at 90, job height at 2, gap voltage at 25, gap current at 1 has high material removal rate is the optimal parameter combination.

Based on the graph obtained for the S/N ratio for the output response Kerf width, the individual optimal values are obtained at A2B2C2D2E1F2G1H2I2J1K1, i.e. pulse on time at 110, pulse off time at 45, input current at 2, wire feed rate at 25, sensitivity at 9, the gap at 14, wire tension at 4, water pressure at 99, job height at 2, gap voltage at 20, gap current at 1 is the optimal set of parameters for kerf width.

From the GRG obtained according to the series of steps followed in the Grey system theory, the above graph is obtained through which the optimal parametric combination set developed in the twelfth experiment i.e., pulse on time at 110, pulse off time at 45, input current at 1, wire feed rate at 20, sensitivity at 10, the gap at 12,

Table 6
Grey relational analysis.

EXPT NO	T ON	T OFF	I/P CUR	WFR	S	G	WT	WP	JH	GV	GC	MRR	KW	GRG	Rank
1	105	40	1	20	9	12	4	90	1	20	1	1730	0.53	0.55	6
2	105	40	1	20	9	14	5	99	2	25	2	1900	0.49	0.54	7
3	105	40	2	25	10	12	4	90	2	25	2	2400	0.64	0.70	3
4	105	45	1	25	10	12	5	99	1	20	2	2560	0.66	0.73	2
5	105	45	2	20	10	14	4	99	1	25	1	2670	0.34	0.51	10
6	105	45	2	25	9	14	5	90	2	20	1	2260	0.31	0.46	11
7	110	40	2	25	9	12	5	99	1	25	1	2800	0.33	0.52	9
8	110	40	2	20	10	14	5	90	1	20	2	2356	0.61	0.67	5
9	110	40	1	25	10	14	4	99	2	20	1	2800	0.14	0.42	12
10	110	45	2	20	9	12	4	99	2	20	2	3270	0.23	0.53	8
11	110	45	1	25	9	14	4	90	1	25	2	3680	0.4	0.68	4
12	110	45	1	20	10	12	5	90	2	25	1	4200	0.5	0.85	1

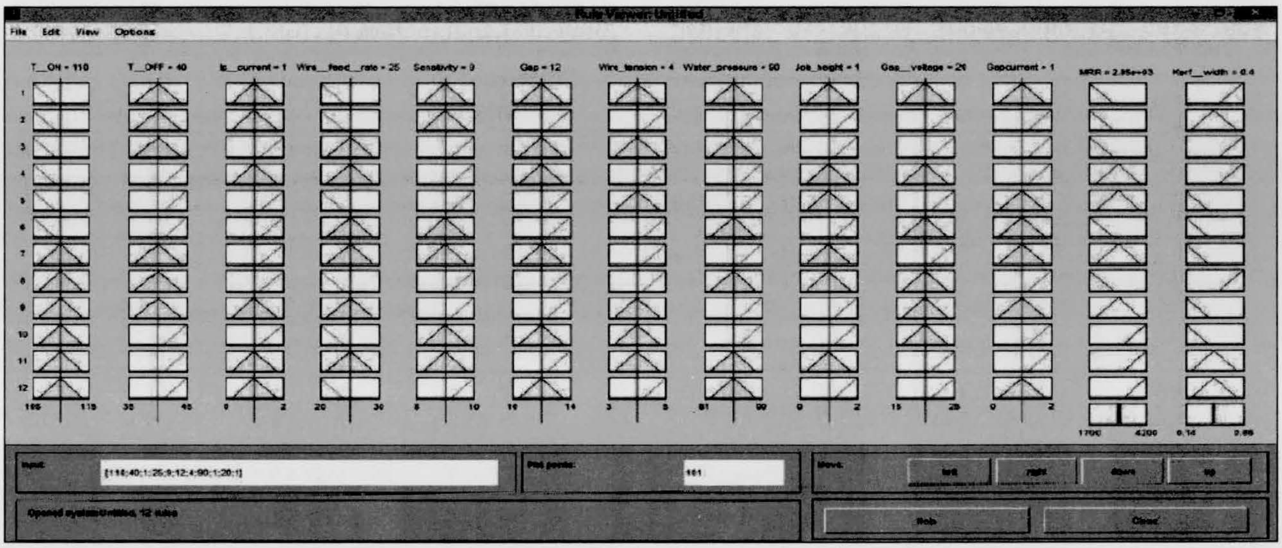

Fig. 7. De Fuzziffication process for the selected values of inputs.

wire tension at 5, water pressure at 90, job height at 2, gap voltage at 25, gap current at 1, and the optimal output parameters obtained are higher MRR at 4200 mm^3/min, lower kerf width at 0.5 mm.

7. Confirmation Test

The exactness of the predicted values to the calculated values can be determined by the confirmation test. Through GRA, the optimal process parameter combination set obtained is A2B2C1D1E2F1G2H1I2J2K1. This twelfth experimental run from the twelve calculated runs is compared with the predicted values obtained by the Fuzzy model in the confirmation test. The predicted values are derived from the following formula 5.

$$M = M_m + \sum_{i=1}^{n}\left(M_0 - M_m\right) \qquad \text{.....................(5)}$$

Where M_m is the total mean of the MRR and KW, and M_o is the mean of the MRR and KW at an optimal level, and n is the number of main design parameters that influence the multiple responses.

From the confirmation test, the best optimal parameter combination set is obtained at pulse

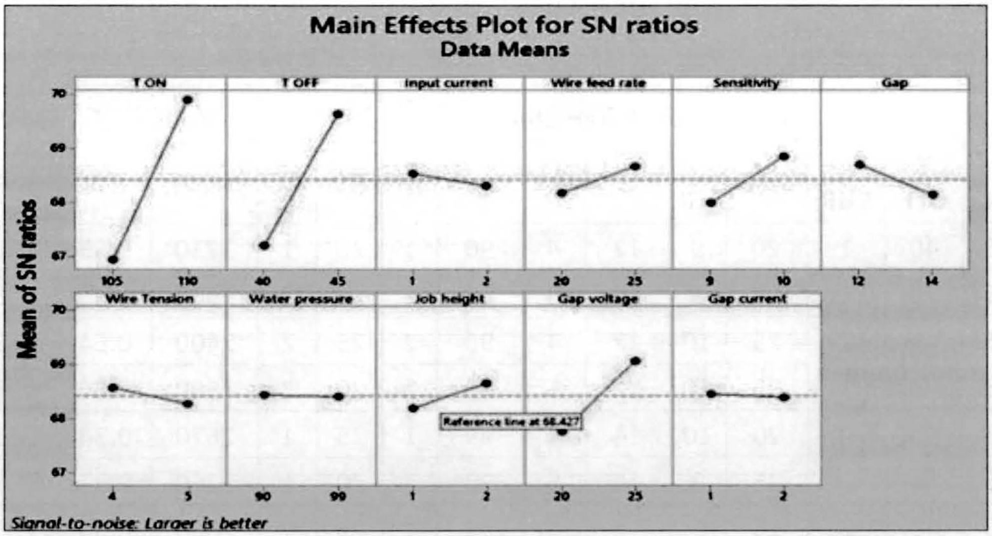

Fig. 8. S/N Ratio graph for MRR.

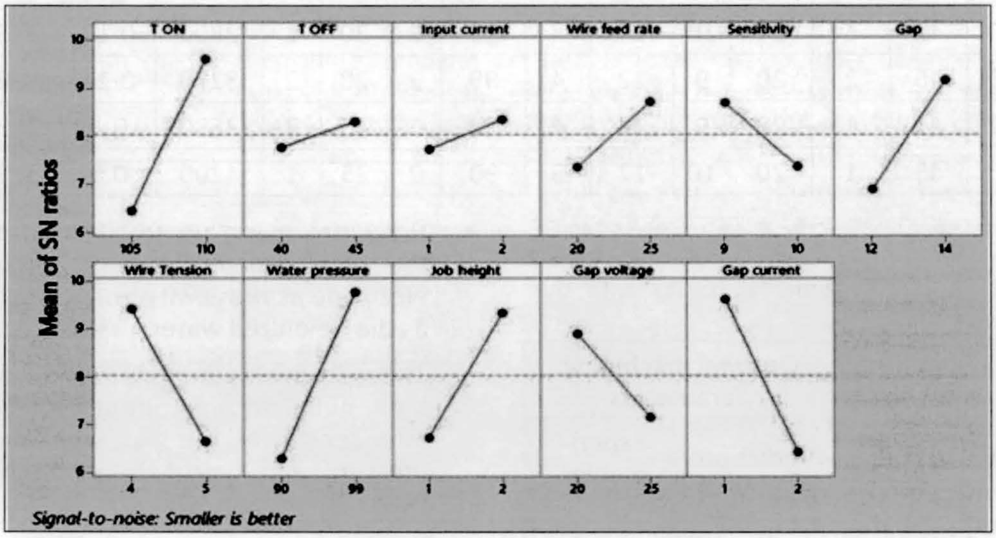

Fig. 9. S/N ratio graph for kerf width.

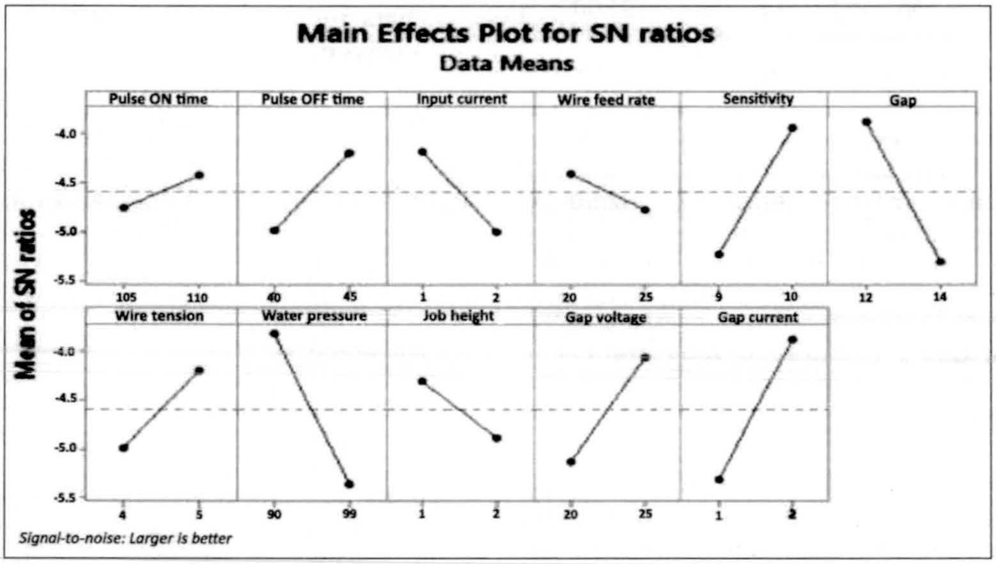

Fig. 10. Response graph for GRG.

Table 7
Variation in the measured and the predicted out put values.

S. NO	Input Process Parameters											Measured		Predicted	
	T ON	T OFF	I/P CUR	WFR	S	G	WT	WP	JH	GV	GC	MRR	KW	MRR	KW
1	105	40	1	20	9	12	4	90	1	20	1	1730	0.53	2030	0.592
2	105	40	1	20	9	14	5	99	2	25	2	1900	0.49	2030	0.4
3	105	40	2	25	10	12	4	90	2	25	2	2400	0.64	2030	0.592
4	105	45	1	25	10	12	5	99	1	20	2	2560	0.66	2950	0.592
5	105	45	2	20	10	14	4	99	1	25	1	2670	0.34	2950	0.208
6	105	45	2	25	9	14	5	90	2	20	1	2260	0.31	2030	0.208
7	110	40	2	25	9	12	5	99	1	25	1	2800	0.33	2950	0.208
8	110	40	2	20	10	14	5	90	1	20	2	2356	0.61	2030	0.592
9	110	40	1	25	10	14	4	99	2	20	1	2800	0.14	2950	0.208
10	110	45	2	20	9	12	4	99	2	20	2	3270	0.23	3880	0.208
11	110	45	1	25	9	14	4	90	1	25	2	3680	0.4	3880	0.4
12	110	45	1	20	10	12	5	90	2	25	1	4200	0.5	3880	0.4

Table 8
Comparison of the experimental results with the predicted results.

	Initial process parameters	Optimal machining parameters	
		Prediction	Experi-mental
Setting level	A2B2C1D1E2 F1G2H1I2J2K	A2B1C1D2E1 F1G1H1I1J1K1	
MRR	4200	2950	2800
Kerf Width	0.5	0.4	0.33
Prediction Error e_p(%)		5.08	17.5
Accuracy (%)		94.92	82.50

on time at 110, pulse off time at 45, input current at 1, wire feed rate at 25, sensitivity at 10, the gap at 12, wire tension at 4, water pressure at 90, job height at 1, gap voltage at 20, gap current at 1.

8. Conclusions

The WEDM machine is used for machining the twelve square-cut profiles on AISI 440C Stainless steel workpiece. The conclusions that can be drawn from the present work are:

- Holes are made up to a complete depth of the workpiece thickness i.e., 6mm using the electrode as brass wire and dielectric medium as the deionized water.
- The machining parameters taken are pulse on time, pulse off time, input current, wire feed rate, sensitivity, the gap, wire tension, water pressure, job height, gap voltage, and gap current.
- Through the variation in the input parameters, the effect on the output desired characteristics such as MRR, Kerf width is analyzed.
- From the S/N ratio graphs obtained from the MINITAB19 software for MRR, the optimal parameters obtained are A2B2C1D2E2F1G1H1I2J2K1 i.e., pulse on time at 110, pulse off time at 45, input current at 1, wire feed rate at 25, sensitivity at 10, the gap at 12, wire tension at 4, water pressure at 90, job height at 2, gap voltage at 25, gap current at 1.
- From the S/N ratio graphs obtained from the MINITAB19 software for Kerf width, the optimal parameters obtained are A2B2C2D2E1F2G1H2I2J1K1 i.e., pulse on time at 110, pulse off time at 45, input current at 1, wire feed rate at 25, sensitivity at 9, the gap at 14, wire tension at 4, water pressure

at 99, job height at 2, gap voltage at 20, gap current at 1.

- From the GRA, the optimal parametric combination set obtained is A2B2C1D1E2 F1G2H1I2J2K1 i.e., pulse on time at 110, pulse off time at 45, input current at 1, wire feed rate at 20, sensitivity at 10, the gap at 12, wire tension at 5, water pressure at 90, job height at 2, gap voltage at 25, gap current at 1.
- Through Fuzzy logic, predicted values are obtained.
- The confirmation test is done to evaluate the exactness of the experimental and predicted values and found it more feasible, and economical.

9. Scope for Future Work

- The accuracy and the precision of the developed model can be improved by considering more parameters and levels
- The fuzzy model can be improved by considering more levels of fuzzy membership functions. In addition, artificially intelligent systems such as the neural networks technique, and simulation techniques might be used to predict the system outputs.

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