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Influence of Process Parameters on Wire EDM Process for AISI 316 Stainless Steel

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***Abstract* – The optimization of wire electrical discharge machining (WEDM) parameters for AISI 316 stainless steel using Taguchi's robust design approach is proposed. Experimentation is planned as per Taguchi's L_{27} orthogonal array. Each experiment has to be performed under different process parameters of pulse on time, pulse off time, pulse peak current, wire tension and wire feed rate. Two responses namely material removal rate and surface roughness (Ra) were considered for each experiment. The optimum machining parameter combination is obtained by using the analysis of signal-to-noise (S/N) ratio. The level of importance of the machining parameters on the material removal rate and surface roughness is determined by using analysis of variance (ANOVA).**

Keywords: WEDM, ANOVA, MRR, Surface roughness, Signal to noise ratio

I. INTRODUCTION

As newer and more exotic materials have been developed in the past few decades, conventional machining operations tend to reach their limitations as relatively more complicated shaped jobs are required to be manufactured. The increased use of wire-cut electrical discharge machining (WEDM) in manufacturing has thus kept growing at a highly accelerated rate since its first industrial application more than 30 years ago. Its broad capabilities have allowed it to encompass production in aerospace and automotive industries and virtually all areas of conductive material machining. This is because wire EDM provides the best alternative, or sometimes the only alternative, for machining conductive, exotic and HSTR (high strength and temperature resistive) material with the scope of generating intricate shapes and profiles. Also, WEDM has proved to have incredible prospective in its applicability in the present day metal cutting industry for achieving a significant dimensional accuracy, surface finish and contour generation trait of products or parts. Wire EDM is a special form of the traditional EDM process in which the electrode is a continuously moving conductive wire. Material is worn from the work piece by a series of distinct sparks between the work piece and the wire electrode (tool) estranged by a thin film of dielectric fluid (deionised water) which is continuously force fed to the machining zone to flush away the eroded particles. The progress of the wire is proscribed numerically to attain the preferred three-dimensional shape and accuracy for the work piece. Although the average cutting speed, relative machining costs, accuracy and surface finish have been improved many times since the commercial inception of the machine, much more improvement is still required to meet the increasing demand of precision and accuracy by different industries.

II. LITERATURE REVIEW

To improve the performance namely the material removal rate, cutting speed, dimensional accuracy and surface roughness of the WEDM process, several researches have attempted previously. Ramakrishnan et al. [7] used Multi Response optimization procedure for studying WEDM operations using Taguchi's robust design of experiments. Experiments were 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, and wire feed speed and ignition current intensity. Three responses namely material removal rate, surface roughness and wire wear ratio (WWR) had been considered for each experiment. Liao et al [3] carried out the study on the machining parameters optimization of WEDM in SKD 11 alloy steel. They used 0.25mm diameter brass wire as electrode. According to Taguchi quality design concept L_{18} orthogonal arrays table was chosen for conducting experiments. A total of six machining parameters like pulse on time, pulse off time, table feed, wire tension, wire speed and flushing pressure were chosen for the controlling factors and each parameter have three levels and the designed machining conditions are evaluated in terms of the measured machining performances like gap width, material exclusion rate, surface coarseness, discharge frequency, gap voltage, normal discharge frequency ratio. Chiang et al [1] used grey relational analysis for their study on aluminium oxide particle reinforced material with multiple performance characteristics.

Ho et al [2] reviewed the WEDM research concerning the optimization of the process parameters survey the influence of the various factors distressing the machining performance and yield. Mahabatra et al.[4] optimized the WEDM process parameters using Taguchi method. In this study the relationship between control factors like discharge current, pulse duration, pulse frequency, wire speed, wire tension and dielectric flow and responses like material removal rate, surface roughness and Kerf were established by means of non linear regression analysis. Shajan Kuriakose et al. [11] conducted multi objective optimization of WEDM process by Non Dominated Sorting Genetic Algorithm technique. Ozdemir et al. [5] performed exploration on machinability of nodular cast iron (GGG 40) by WEDM. Variation of the surface roughness and cutting rate with machining parameters were scientifically modeled by using the regression analysis method. Puri et al [6] made an attempt to model the white layer depth through response surface methodology. Tarang et al. [10] used feed forward neural network approach to determine the optimal cutting parameters while machining SUS-304 stainless steel in WEDM. Speeding et al [10] performed the modeling process through response surface methodology and artificial neural networks. A response surface model based on a central composite rotatable experimental design, and 4-16-3 size back propagation neural networks have been developed. Speeding et al [10] performed the modeling process through response surface methodology and artificial neural networks. A response surface model based on a central composite rotatable experimental design, and 4-16-3 size back propagation neural networks have been developed. Shajan kuriakose et al [11] conducted multi objective optimization of WEDM process by non dominated sorting genetic algorithm technique. They established that influence of the parameters on the cutting velocity and the surface finish are quiet contrary. Tarang et al [13] used feed forward neural network approach to determine the optimal cutting parameters while machining SUS 304 stainless steel in WEDM. The disparity of surface roughness and MRR with machining parameters and optimization of machining setting for minimum surface roughness and maximum MRR should be investigated experimentally and the obtained results should be interpreted and modeled statistically to understand closely the behavior of machining rate and accuracy in WEDM.

In this cram, the upshot of the machining parameters and their level of consequence on the surface roughness and the MRR are statistically evaluated by using analysis of variance (ANOVA). Also, an optimization study is introduced for the case of low surface roughness and high MRR.

Experiments were conducted underneath diverse machining parameters, namely, pulse on time, pulse off time, discharge current, wire tension and wire feed rate. The settings of machining parameters were determined by using Taguchi experimental design method.

III. EXPERIMENTAL DETAILS

A. Machine tool, material and Measurement

The experimental studies were performed on a ELEKTRA OPTICUT 434 WEDM machine tool. Different settings of pulse on time, pulse off time, discharge current, wire tension and wire feed rate were used in the experiments as specified in Table

TABLE 1
EXPERIMENTAL SETTINGS

Sl. No.	Control factors	Unit	Range			Level		
			Symbol	Actual	Decided	1	2	3
1	Pulse on time	µsec	A	1 - 10	4 – 6	4	5	6
2	Pulse off time	µsec	B	1 - 10	4 – 6	4	5	6
3	Pulse peak current	amps	C	0- 30	2 – 5	2	3.5	5
4	Wire tension	gm	D	200 – 1500	600 – 1000	600	800	1000
5	Wire feed rate	m/min	E	0 – 10	3 – 5	3	4	5

TABLE 2
CHEMICAL COMPOSITION OF AISI 316 STAINLESS STEEL

Elements	C	Cr	Ni	Mo	Mn	Si	P	Fe
% (Wt.)	0.128	16.31	9.63	1.733	1.344	0.661	0.032	Balance

The mean cutting speed data (Cs) was observed directly from the machine tool monitor. Generally during this process the wire diameter is kept constant. Therefore, the width of cut (W) remains constant. The MRR for the WEDM operations using Eqn. 1 which is shown below:

$$MRR = Cs \times L \quad (1)$$

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

B. Design of experiment based on Taguchi method

To evaluate the effects of machining parameters on performance characteristics (surface roughness and MRR), and to identify the performance characteristics under the optimal machining parameters, a specially designed experimental procedure is required. Conventional investigational design methods are too complex and difficult to use. Additionally, large number of experiments has to be carried out when number of machining parameters increases. In this study, Taguchi method, a powerful tool for parameter design of performance characteristics, was used to determine optimal machining parameters for minimum surface roughness and maximum MRR in WEDM. In Taguchi method, process parameters which influence the products are separated into two main groups: control factors and noise factors. The control factors are used to select the best conditions for stability in design of manufacturing process, whereas the noise factors denote all factors that cause variation. Taguchi projected to get hold of the characteristic data by means of orthogonal array, and to explore the recital measure from the data to decide the optimal process parameters. This scheme uses an unusual plan of orthogonal arrays to cram the whole constraint space with petite number of experiments only. In this study, five machining parameters were used as control factors and each parameter was designed to have three levels, denoted 1, 2 and 3 [14, 15, 16] . According to the Taguchi quality design concept, a L27 orthogonal array table with 27 rows, analogous to the number of experiments as preferred for the experiments and the consequences are presented in Table 3.

TABLE 3

ORTHOGONAL ARRAY FOR L27(313) TAGUCHI DESIGN

L_{27} (3^{13})	A Pulse on time µsec	B Pulse off time µsec	C Pulse peak Current amps	D Wire tension gm	E Wire feed rate m/min	MRR mm^2/min	SR (µm)
1	4	4	2	600	3	17	3.20
2	4	4	3.5	800	4	21	3.64
3	4	4	5	1000	5	24	3.97
4	4	5	3.5	800	4	15	3.42
5	4	5	5	1000	5	24	3.77
6	4	5	2	600	3	15	4.02
7	4	6	5	1000	5	26	3.88
8	4	6	2	600	3	11	3.43
9	4	6	3.5	800	4	25.5	3.76
10	5	4	2	800	5	18	3.55
11	5	4	3.5	1000	3	23	3.52
12	5	4	5	600	4	27	3.49
13	5	5	3.5	1000	3	23	3.89
14	5	5	5	600	4	24	3.75
15	5	5	2	800	5	16	3.26
16	5	6	5	600	4	25	3.55
17	5	6	2	800	5	19	3.38
18	5	6	3.5	1000	3	22	3.28
19	6	4	2	1000	4	24	3.75
20	6	4	3.5	600	5	23	3.64
21	6	4	5	800	3	27	3.68
22	6	5	3.5	600	5	24	3.78
23	6	5	5	800	3	19	3.76
24	6	5	2	1000	4	17	3.74
25	6	6	5	800	3	27	3.78
26	6	6	2	1000	4	19	3.75
27	6	6	3.5	600	5	21	3.76

IV. ANALYSIS AND DISCUSSION OF EXPERIMENTAL RESULTS

The analysis of variance (ANOVA) was used to found statistically noteworthy machining parameters and the percent contribution of these parameters on the surface roughness and the MRR. In Taguchi method [8], a loss function is used to estimate the variation among the investigational value and the preferred value. This loss function is further malformed in to a signal-to-noise (S/N) ratio. There are numerous S/N ratios existing depending on the type of characteristics; lower the better (LB), nominal is the best (NB), and higher is better (HB). In WEDM, the lower surface roughness and higher MRR are the sign of better performance. For the HB and LB, the definition of the loss function (L) for machining performance results (MRR, surface roughness) of n repetitive number are :

$$L_{HB} = 1/n\sum_{i=1}^{n} 1/Y^2{}_{MRR} \qquad (2)$$

$$L_{LB} = 1/n\sum_{i=1}^{n} Y^2{}_{SF} \qquad (3)$$

Where Y_{MRR} and Y_{SF} are the response for material removal rate and surface finish correspondingly and n denotes the number of experiments. The S/N ratio can be calculated as a logarithmic conversion of the loss function as shown below:

S/N ratio for MRR = -10 log 10 (LHB) (4)

S/N ratio for SF = -10 log 10 (LLB) (5)

Despite the consequences of the sort of the performance characteristics, a greater S/N value corresponds to a better performance. Therefore, the best possible level of the machining parameters is the level with the greatest S/N ratio value. By applying the Eqns. (2) – (5), the S/N ratio values for each experiment of L27 (Table 3) was calculated (Table 4 and 5). Based on the analysis of S/N ratio, the optimal machining performance for the MRR was obtained at 6 µsec. pulse on time (Level 3), 4 µsec. pulse off time (Level 1), 5 amps. Pulse peak current (Level 3), 1000 g. wire tension (Level 3) and 4 m/min. wire feed rate (Level 2) settings. Fig. 1 shows the effect of machining performance on the MRR. The optimum machining performance for the surface finish was obtained at 5 µsec. pulse on time (Level 2), 4 µsec. pulse off time (Level 1), 2 amps. Pulse peak current (Level 1), 800 g. wire tension (Level 2) and 3 m/min. wire feed rate (Level 1) settings. Fig. 2 shows the upshot of machining performance on the surface finish.

TABLE 4

S/N RATIO VALUES MRR

Machining parameter	Mean S/N ratio by factor level (dB)		
	Level 1	Level 2	Level 3
A	25.62	26.70	26.88
B	27.01	25.71	26.48
C	24.61	26.74	27.84
D	26.05	26.19	26.96
E	25.90	26.68	26.62

Overall mean = 26.398 dB

TABLE 5

S/N RATIO VALUES FOR SURFACE FINISH

Machining parameter	Mean S/N ratio by factor level (dB)		
	Level 1	Level 2	Level 3
A	-11.2865	-10.9151	-11.4516
B	-11.1236	-11.3720	-11.1580
C	-11.0180	-11.1920	-11.4440
D	-11.1680	-11.0690	-11.4160
E	-11.1457	-11.2407	-11.2669

Overall mean = -11.2272 dB

A better feel for the relative effect of the different machining parameters on the MRR and the surface finish was obtained by disintegration of variance, which is called analysis of variance (ANOVA). The virtual significance of the machining parameters with respect to the MRR and the surface finish was investigated to determine more accurately the optimum combinations of the machining parameters by using ANOVA. The results of ANOVA for the machining outputs are presentedin Tables 6 and 7. Statistically, F-test provides a verdict at some confidence level as to whether these estimates are significantly different. Larger F-value indicates that the variation of the process parameter makes a big change on the performance characteristics. F-values of the machining parameters are compared with the fitting confidence table.

According to this analysis, the most effective parameter with respect to MRR is pulse peak current. Pulse on time and pulse off time are found as statistically significant factors, whereas the effect of wire tension and wire feed rate on the MRR was insignificant. Percent contribution indicates the relative power of a factor to reduce variation. For a factor with a high percent contribution, a small variation will have a great influence on the performance. The percent contributions of the machining parameters on the MRR are shown in Table 6. According to Table 6, pulse peak current was found to be the major factor affecting the MRR (67.089%), whereas pulse on time was found to be the second ranking factor (11.573%) and pulse off time was start to be the third grade reason (10.718). The percent involvement of wire tension and wire feed rate are minor, being 5.9797% and 4.642% correspondingly. According to F-test analysis, the momentous parameters on the MRR are open circuit voltage, pulse on time and pulse off time. During the above examination the optimal machining parameters identified for MRR are A3B1C3D3E2.

The percent contributions of the machining parameters on the surface finish are shown in Table 7. According to Table 7, pulse on time is found to be the major factor affecting the surface finish (44.667%). The pulse peak current, wire tension and pulse off time are considered as significant factors with the percent contribution on the surface finish are 23.484, 18.73 and 10.723% respectively. The wire feed rate considered statistically insignificant, because it has a very low F value and percent contribution (2.3958%). Therefore this is included in the error term. Based on the above results the optimal cutting conditions obtained for surface finish are A2B1C1D2E1.

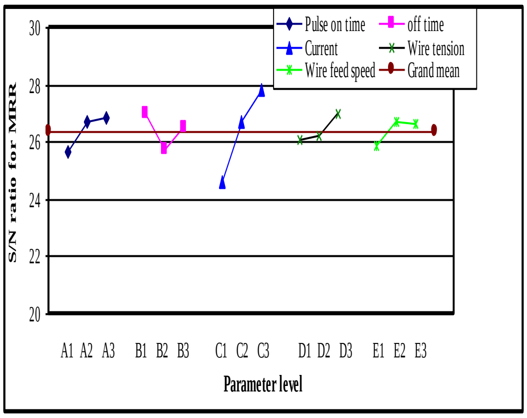

Figure 1. The effect of machining parameters on MRR

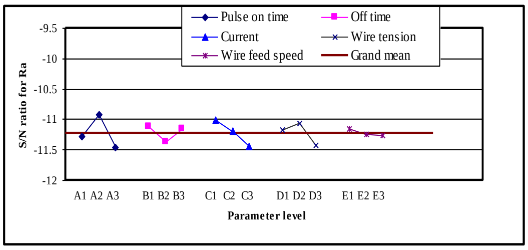

Figure 2. The effect of machining parameters on surface finish

TABLE 6
RESULTS OF ANOVA FOR MRR

Machining Parameters	Degrees of freedom	Sum of square	Mean square	F test	% Contribution
A	2	8.3491	4.1745	2.4928	11.5725
B	2	7.7324	3.8662	2.3087	10.7177
C	2	48.401	24.2009	14.451	67.0886
D	2	4.3135	2.1567	1.2879	5.9788
E	2	3.3491	1.6745	1	4.6422

TABLE 7
RESULTS OF ANOVA FOR SURFACE FINISH

Machining Parameters	Degrees of freedom	Sum of square	Mean square	F test	% Contribution
A	2	1.4826	0.7413	18.6436	44.66714
B	2	0.3559	0.1779	4.4757	10.72307
C	2	0.7795	0.3897	9.8021	23.48443
D	2	0.6216	0.3108	7.8175	18.72953
E	2	0.0795	0.0397	1	2.395834

V. CONFIRMATION EXPERIMENT

The confirmation experiment is the final step of the Taguchi's design of experiment process after selecting the optimal parameters. The purpose of the confirmation experiment is to validate the conclusions drawn during the analysis phase. In this learning, behind determining the most favorable situation and predicting the rejoinder under these conditions, a new experiment was planned and conducted with the optimum levels of the machining parameters. The concluding step is to envisage and validate the enhancement of the performance characteristic. The predicted S/N ratio η_{opt} using the best possible levels of the machining parameters can be calculated as:

$$\eta_{opt} = \eta_m + \sum_{i=1}^{p} (\overline{\eta}_i - \eta_m) \tag{6}$$

where η_m is total mean of S/N ratio, η_{opt} is the mean of S/N ratio at the optimal level, and p is the number of chief machining parameter that appreciably concern the performance. The results of experimental confirmation using optimal machining parameters are shown in Tables 8 and 9.

Table 8 shows the assessment of the predicted MRR with the authentic MRR using most favorable machining parameters. The improvement in S/N ratio from the starting machining parameters to the level of optimal machining parameters is 0.7903 dB. The MRR is increased by 1.0952 times. So, the MRR is greatly improved by using the approach. Table 9 shows the comparison of the predicted surface finish with the actual surface finish using the optimal machining parameters. The enhancement in *S*/*N* ratio from the starting machining parameters to the optimal machining parameters is 0.7726 dB. The surface roughness is decreased by 1.093 times. The experimental results inveterate the validity of used Taguchi method for enhancing the machining performance and optimizing the machining parameters. The MRR and the surface finish are significantly enhanced by using the approach.

TABLE 8
RESULTS OF THE CONFIRMATION EXPERIMENT FOR MRR

	Initial cutting parameters	Optimal cutting parameters	
		Prediction	Experiment
Level	A2B2C2D2E2	A3B1C3D3E2	A3B1C3D3E2
Material removal rate (mm2/min)	21		23
S/N ratio (dB)	26.4443		27.2346

Improvement in S/n ratio for MRR = 0.7903 dB

TABLE 9
RESULTS OF THE CONFIRMATION EXPERIMENT FOR SURFACE FINISH

	Initial cutting parameters	Optimal cutting parameters	
		Prediction	Experiment
Level	A2B2C2D2E2	A2B1C1D2E1	A2B1C1D2E1
Surface roughness (µm)	3.76		3.44
S/N ratio (dB)	-11.5038		-10.7312

Improvement in S/N ratio for surface finish = 0.7726 dB

VI. CONCLUSION

This paper has offered an exploration on the optimization and the consequence of machining parameters on the MRR and the surface finish in WEDM operations. The outcome of various machining parameter such as pulse on time, pulse off time, pulse peak current, wire tension, and wire feed speed has been premeditated during the machining of AISI 316 stainless steel. The level of consequence of the machining parameters on the MRR and the surface finish is determined by using ANOVA. Based on ANOVA method, the greatly effectual parameters on both the MRR and the surface finish were found as pulse peak current and pulse on time other than the added parameters considered in this study. The results showed that pulse peak current was about six times imperative than the second graded factor (pulse on time) for controlling the MRR, whereas pulse on time for controlling the surface finish was about two times more significant than the second ranking factor (pulse peak current). An optimum parameter blend for the maximum MRR and minimum surface roughness was obtained by using the analysis of signal-to-noise(S/N) ratio. The confirmation tests indicated that it is probable to augment MRR and diminish surface roughness appreciably by using the projected statistical technique. The experimental results inveterate the validity of the used Taguchi method for enhancing the machining performance and optimizing the machining parameters in WEDM operations.

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