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Application of Orthogonal Array Technique and Simulated Annealing Algorithm in Surface Modification When EDM Hot Worked Steel

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Abstract

The last decade has seen an increasing interest in the novel applications of electrical discharge machining (EDM) process, with particular emphasis on the potential of this process for surface modification. Besides erosion of work material during machining, the intrinsic nature of the process results in removal of some tool material also. This paper proposes an optimization methodology for the selection of best process parameters in electro discharge machining for surface modification of 40CrMnMoS86 hot worked steel parts. The experimental data are gathered based on Taguchi L36 design matrix. The tests are conducted under varying peak current (I), voltage (V), pulse on time (Ton), pulse off time (Toff) and duty factor (η).The effects of these input parameters are then determined on the most important process output response, surface roughness (SR). Using these data and the simulated annealing algorithm, the process parameters can be set to achieve desired surface roughness. Next, analysis of variance (ANOVA) and F–test have been used to evaluate the relative significance of process variables affecting process outputs. A verification test is also performed to verify the accuracy of optimization procedure in determining the optimal levels of machining parameters. The results indicate that Taguchi technique and simulated annealing algorithm are quite efficient in determining optimal process parameters for optimization of surface finish in EDM.

Keywords: Taguchi technique, Electrical Discharge Machining, Optimization, simulated annealing algorithm (SA), Analysis of variance

1. Introduction

Electric-discharge machining (EDM) is a non-conventional, thermo-electric process in which the material from work piece is eroded by a series of discharge sparks between the work and tool electrode immersed in a liquid dielectric medium. These electrical discharges melt and vaporize minute amounts of work material, which are then ejected and flushed away by the dielectric. This technique has been widely used in modern metal working industry for producing complex cavities in dies and moulds, which are otherwise difficult to create by conventional machining. EDM can provide an effective solution formachining hard conductive materials and reproducing complex shapes. EDM involves the phenomena such as: spark initiation, dielectric breakdown, thermo-mechanical erosion of metals [1]. A schematic illustration of EDM process is given in Figure 1.

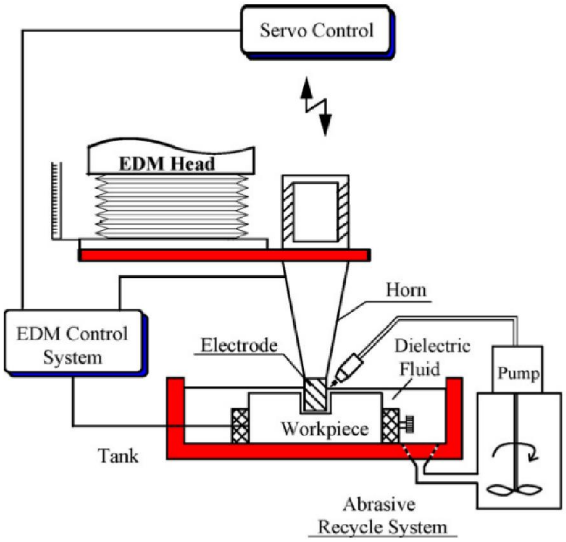

Fig.1 Schematic illustration of Electrical Discharge Machining [2]

Metal removal process in EDM is characterized by nonlinear, stochastic and time varying characteristics. In EDM, a quantitative relationship between the operating parameters and controllable input variables is often required. Many regression techniques have been used for modeling the EDM process. Neural networks and fuzzy systems form an alternative approach to generalize the experimental results and develop the system model accurately [1].

Howevere, EDM is a costly process and hence proper selection of its process parameters is essential to increase production rate and improve product quality.

EDM technique is specially useful when the workpiece is hard, birttle and requires high surface finish. Therefore, the merits of the EDM technique become most apparent when machining such material as 40CrMnMoS86 hot worked steel parts which have very high hardness in reinforcement. In addition, mechanical and physical properties of hot worked steel such as hardness, toughness and high wear resistance, has made it an important material for engineering components particularly in making moulds and dies [1,2].

Like any other machining processes, the performance of EDM is significantly affected by its process parameter settings. Important process parameters in EDM are peak current (I), voltage (V), pulse on time (T_{on}), pulse off time (T_{off}) and duty factor (η) [3-5]. These parameters, in turn, determine the process output characteristic, among which Surface Roughness (SR) is the most important one.

The superior performance of EDM than traditional machining technology has already been proved in applying toward the materials with high strength, high hardness or more complicated shapes. Since the mechanism of EDM is done by melting the unwanted parts of workpiece by high temperature spark, many defects such as porosity, cracks, improper recast layer, residual stress are easily found on the workpiece surface due to the rapid high temperature melting and cooling process during EDM. Thus, a comprehensive study to improve the surface roughness of EDMed workpiece is the crucial topics. Many studies have noticed this unavoidable effect in EDM applications and have also proposed many prescriptions to fulfill the various criteria of industrial demanding. For instance, Mohri et al. [6-8] demonstrated that by adding powder into dielectric via EDM process, a mirror-like surface could be achieved. Luo et al. [9] suggested that either the low peak current or theshort pulse duration for EDM could gain a better surface roughness in machining process. Narumiya et al. [10] improved the surface roughness of workpiece by optimizing various combinations of powder added into dielectric. Saito et al. [11,12] added conductive powders into dielectric to gain a better surface roughness on a large surface area of workpiece in EDM process.

Kiyak and Cakır [13], have studied the effects of EDM parameter levels on surface roughness for machining of 40CrMnNiMo864 tool steel (AISI P20) which is widely used in the production of plastic mold and die. It is observed that Surface roughness increases with increasing pulsed current and pulse time. Low current and pulse time produces minimum surface roughness that means good surface finish quality. The selection of these machining parameters is not useful because machining process generally becomes very slow. Material removal rate will be low and thus machining cost increases. This combination should be used in finish machining step of EDM process.

In recent years, statistical analysis and Design of Experiments (DOE) technique have increasingly been employed to establish the relationships between various process parameters and the process outputs in variety of manufacturing industries [1-5].

In this study the effects of EDM parameter levels on 40CrMnMoS86 hot worked steel have been investigated. As mentioned earlier, SR, is the most important performance characteristic in EDM. In turn, these output characteristic is determined by the process parameter settings, such as peak current (I), voltage (V), pulse on time (T_{on}), pulse off time (T_{off}) and duty factor (η).

The main objectives of the present study are: 1) to establish the relationship between EDM process parameters and the process output characteristic, and 2) to determine the optimal parameter levels for minimum surface roughness by application of simulated annealing algorithm. The proposed procedure is based on statistical analysis of the experimental data. The article concludes with the verification of the proposed approach and a summary of the major findings.

2. Experimental Procedure And Designe Of Experiments (Doe)

In the present study, an Azerakhsh-304H die-sinking machine has been used to perform the experiments (Figure 2). The test specimens were of 40CrMnMoS86 hot worked steel. A total of 4 tests were performed on each samples, two tests on each side.

The electrodes were made of 16mm cylindrical shape copper. The pure kerosene was used as the dielectric fluid in all experiments. The 36 sets of data needed for modeling, are obtained using L_{36} Taguchi matrix. The Process parameters and levels used in the experiment, experimental set up and conditions are given in the Tables 1 and 2. Table 2 lists the machining parameters range of changes. As show, pulse off time is considered at two levels, while all other process variables have three levels.

Table 1 Experimental set up and conditions.

Equipment	Specification	
Machine tool	EDM (Azarakhsh 304H), Cross Travel 300×250, 7kw, Iran	
Work specimen material	2312 (40CrMnMoS86) hot worked steel with dimensions of 40×20×10 mm	
Electrode	Copper (99.8% purity and 8.98 g/cm3 density) with dimensions of Φ16×60 mm	
Roughness tester	Surtronic 3+ with 0.1 accuracy, R_a, German	
Weighing machine	A&D, with 0.01 accuracy, Japan	
Dielectric	pure kerosene	

Table 2 Design scheme of experimental parameters and levels for EDM

No.	Symbols	Factors	Units	Level			
				Range of changes	1	2	3
1	A	Pulse off time (T_{off})	µS	10 – 75	10	75	-
2	B	Pulse on time (T_{on})	µS	25 – 200	25	100	200
3	C	Peak current (I)	A	2.5 – 7.5	2.5	5	7.5
4	D	Duty factor (η)	S	0.4 – 1.6	0.4	1	1.6
5	E	Voltage (V)	V	50 – 60	50	55	60

The SR is considered as the performance characteristic to evaluate the machining quality.

The machining time for each test was 45 minutes. Furthermore, the experiments have been done in random order to increase accuracy.

Fig. 2 Die-sinking EDM machine used for experiments

After machining, the surface finish of each specimen was measured with an automatic digital Surtronic (3+) *SR* tester (Figure 3).

Fig. 3 Digital surface roughness tester and electronic balance

3. Analysis And Disscusion Of The Experimental Result

3.1. Signal to noise analysis

Taguchi method uses design of experiments to study the entire parameters space with small number of experiments [14]. It also makes use of signal–to–noise (*S/N*) ratios as performance measures to optimize the output quality characteristic against such variations in noise factors. In this method, a loss function is defined to calculate the deviation between the experimental value and the desired value. This loss function is further transformed into *S/N* ratio. Based on the process under consideration, the *S/N* ratio calculation may be decided as "the Larger the Better, (LB)" or "the Smaller the Better, (SB)" as are given in the following equations [13]:

$$LB : S/N = -10 Log\left(\frac{1}{m}\sum_{i=1}^{m}\frac{1}{y_i^2}\right) \quad (1)$$

$$SB : S/N = -10 Log\left(\frac{1}{m}\sum_{i=1}^{m}y_i^2\right) \quad (2)$$

In the above, S/N is the ratio calculated from the observed values, y_i represents the experimentally observed value of the i^{th} experiment, and m is the repeated number of each experiment. Since the SR is the measure of performance in EDM process, the SB criterion is selected for SR.

The matrix of experimental tests (L_{36}), result of SR and its corresponding S/N ratio are shown in Table 3.

Table 3 Experimental lay out (L_{36}), results of *SR* and *S/N* ratio

No.	T_{off}	T_{on}	I	η	V	SR (μm)	S/N (SR)
1	1	1	1	1	1	3.9	-11.821
2	1	2	2	2	2	7.1	-17.025
3	1	3	3	3	3	13.5	-22.606
4	1	1	1	1	1	3.2	-10.103
5	1	2	2	2	2	6.9	-16.777
6	1	3	3	3	3	12.7	-22.076
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
31	2	1	3	3	3	4.9	-13.803
32	2	2	1	1	1	6.3	-15.986
33	2	3	2	2	2	8.8	-18.889
34	2	1	3	1	2	4.9	-13.803
35	2	2	1	2	3	5.5	-14.807
36	2	3	2	3	1	9.8	-19.824

3.2 Regression modeling

Many problems in engineering and science involve exploring the relationships between two or more variables. Regression analysis is a statistical technique that is very useful for these types of problems [15]. Regression models can be used to predict the behavior of input variables (independent variables) and output responses. In this paper, the output response is *S/N*'s associated with experimental tests. In this study, various regression functions have been fitted on the data given in Table 3. Among these models, quadratic regression model was found to be the most appropriate in terms of estimating the real process. Eq. (3) shows the adjusted second order regression model for EDM process:

$$S/N = -9.11 + 0.0517\, T_{on} - 4.92\, \eta + 0.000149\, T_{on}^2 + 0.00527\, I^2 - 0.00101\, T_{on} \times I - 0.000460 I \times V + 0.0901\, \eta \times V \quad (3)$$

3.3 Analysis of variance (ANOVA)

Analysis of variance (ANOVA) is a mathematical way to determine precision of modeling for a group of observations, which shows how the proposed model fits with experimental results [10]. ANOVA has been performed on the above model to assess their adequacy, within the confidence limit of 95%. ANOVA results indicate that the model is adequate within the specified confidence limit. The calculated determination coefficient (R^2) for this model is 95.2%. Result of ANOVA is shown in table 4.

Table 4 Result of ANOVA for signal to noise ratio (S/N)

Machining parameters	Degree of freedom (Dof)	Sum of square (SS_j)	Adjusted (SS_j)	F-Value
A	1	2.937	2.937	2.62
B	2	246.909	246.909	110*
C	2	113.621	113.621	50.62*
D	2	2.021	2.021	0.90
E	2	4.104	4.104	1.83
Error	26	29.181	29.181	-
Total	35	398.771	-	-

*Significant Parameters
$F_{0.05,1,26} = 4.23$ & $F_{0.05,2,26} = 3.37$

According to ANOVA procedure, large F–value indicates that the variation of the process parameter makes a big change on the performance characteristics. In this study, a confidence level of 95% is selected to evaluate parameters significances [15].

The percent contribution of the EDM parameters on signal to noise ratio (S/N) is shown in Figure 4. According to Figure 4, pulse on time is the major factor affecting the S/N with 62% contribution. Whereas peak current, pulse off time, duty factor and voltage have smaller effects on S/N with 29%, 1%, 0.5% and 0.5% contributions, respectively. The remaining (7%) effects are due to noise factors or uncontrollable parameters.

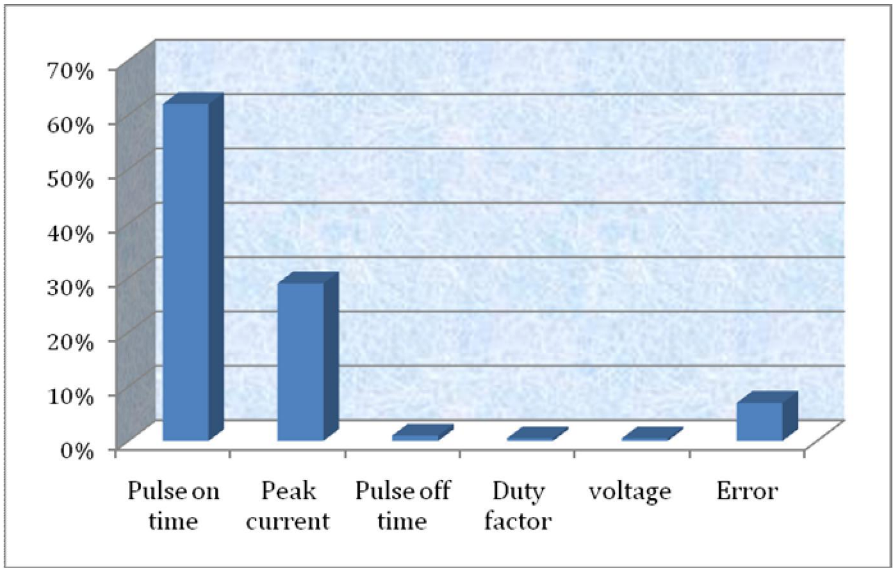

Fig.4 The effect of machining parameters on signal to noise (S/N)

4. SIMULATED ANNEALING ALGHORITH

Once the process model is ready, the optimum process parameters have to be determined. Unlike other non-conventional optimization schemes, Simulated Annealing (SA) process uses single point search method. This algorithm begins with an initial reasonable solution in solution field. Then a new solution in neighborhood of initial solution is formed. If the objective functions value of this new condition be better than initial value or the probability function implemented in *SA* has a higher value than a randomly generated number between zero and one, *SA* accepts this solution. The probability function implemented in *SA* given as follows [16].

$$P = \exp\left(\frac{\Delta F}{T_i}\right) \quad (4)$$

ΔF is absolute difference between the objective function of the current solution and the new solution in each step and Ti is system's temperature. In *SA*, T_i is updating corresponding to annealing coefficient (λ) and according to relationship:

$$Ti+1=\lambda T_i \quad , i= 0, 1\ldots n \qquad \text{and} \quad 0.8 < \lambda < 1 \quad (5)$$

Small amount of λ accelerates algorithm convergence, but larger amounts increases fortune of non healing solutions acceptance. In optimization of developed multi objective model, every solution is a combination of peak current (I), voltage (V), pulse on time (T_{on}), pulse off time (T_{off}) and duty factor (η). Figure 5 shows Simulated Annealing algorithm's performance in optimal solution finding.

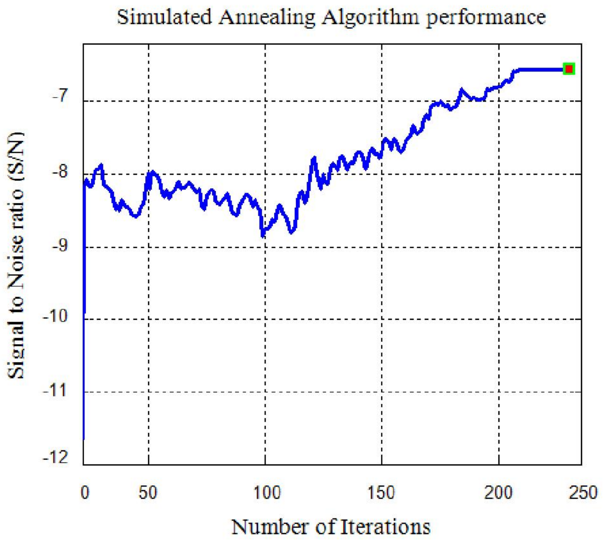

Fig.5 Simulated Annealing Algorithm performance

5. CONFIRMATION EXPERIMENT

To evaluate the adequacy of the proposed approach and statistical analysis, a verification test has been carried out based on the predicted value. The optimal levels of the process parameters are predicted based on *S/N* ratios given in Table 3. These settings should result in *S/N* ratios of -6.4. Table 5 shows the comparison between the predicted and experimental results using optimal process parameters. As indicated, the differences between predicted and actual process output is only 6.2%. Given the nature of EDM process and its many variables, these results are quite acceptable and prove that the experimental results are correlated with the estimated value.

Table 5 Results of confirmation experiments

S/N for Surface Roughness	Optimal condition			
	Prediction	Experiment	Difference	Error (%)
	-6.4	-6.8	0.4	6.2
Parameter setting (T_{off} = 20µs, T_{on} = 45 µs, I = 2.5 A, η = 0.4S, V = 60V)				

6. CONCLUSION

Optimizing the process parameters is a significant step to achieve high quality product with desired output characteristics. In this study a Taguchi based procedure has been employed to optimize EDM process parameter (surface roughness) for machining of 40CrMnMoS86 hot worked steel parts. Taguchi experimental design can effectively reduce the experimental sample size and determine significant factors Statistical analysis reveals that the proposed regression model can accurately represent the actual process. Then a SA technique was employed to find optimal set of process parameters (T_{off} = 20µs, T_{on} = 45 µs, I = 2.5 A, η = 0.4S, V = 60V). The experimental result for the optimal setting shows that there is considerable improvement in the surface roughness therefore the proposed approach is quite capable in predicting EDM process output.

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