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Regression and Statistical Analysis of Process Parameters on Heat Affected Zone in Electrical Discharge Machining of Tool Steel

Saad K. Shather [a], Shukry H. Aghdeab [b], Waqass S. Khudier [c*]

[a] Production Engineering and Metallurgy, Baghdad, Iraq. drengsaad_k_sh@yahoo.com

[b] Production Engineering and Metallurgy, Baghdad, Iraq. shukry_hameed@yahoo.com

[c] Production Engineering and Metallurgy, Baghdad, Iraq. 70127@uotechnology.edu.iq

*Corresponding author.

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KEYWORDS

Electrical Discharge Machining (EDM), Heat Affected Zone and Response Surface Methodology.

ABSTRACT

The presented study has the aim of finding out the relationships between input variables and process parameters that describe mathematical models, also to estimate the impact of independent parameters on the Heat Affected Zone (HAZ). In the presented paper, A2-Tool Steel material is the utilized workpiece material, whereas copper is the electrode material. RSM, which is the abbreviation of Response Surface Methodology, is used for identifying the impact of controllable parameters; such controllable effects consist of pulse current, pulse on time, and pulse off time on HAZ. It has been noticed that model has been developed by RSM adequacy is suitable since the coefficient related to the determination is considered closest to one for HAZ, whereas the highest percentage of error between experimental and predicted data is (-13.829%). From ANOVA, the pulse current has the most significant factor affected on HAZ with 67.219% contribution.

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1. Introduction

In EDM, the material is going to be eliminated through melting and vaporizing by all-electric discharges, electrically conductive materials have been machined via accurately sparks at high pressure and temperature between a workpiece and an electrode in the dielectric medium [1]. This is why the machined surface consists of layers that have been thermally damaged that include the white layer and the heat-affected zone. In such different layers, an observation will be conducted on the residual stresses and micro cracks [2].

The region of the machined surface that did not melt during electrical discharge but has experienced a phase transformation called HAZ [3]. An annealed heat affected zone lay directly below the white layer. HAZ left behind by the EDM process is less hard than the underlying material. This annealed zone could weaken precipitately and root to the fracture stress that could lead to catastrophic failure [4]. Starting from the machined surface and then move downward in the direction of the parent metal, microhardness was determined at altered positions in the cross-section of a machined surface, when reaching a constant value of the microhardness, no thermal altered in this section of machined surface (parent metal).

The HVS-1000 microhardness tester manual (LARYEE Testing Machine) has been utilized to measure hardness.

Kar et al. [5] examined the impact of variables, EDM variables namely (peak current, pulse duration, and discharge voltage), on the following responses. The authors reveal that the discharge current is the most significant parameter that affects the responses when compared with the other inputs. Mishra et al. [6] Taguchi method was utilized to carry out the optimization of parameters and performance characteristics. The pulse current, pulse duration, and gap voltage are considered as input process variables to study the EDM machined surface. The results show that cracks are observed on the machined surface due to internal stresses caused by heating and sudden cooling of a surface.

Morankar and Shelke [7] have presented a model by using RSM, as regards peak current, pulse on time, gap voltage to evaluate the metal removal rate (MRR), and surface roughness (SR). The results indicate that the peak current and the pulse on time have a prominent impact on the values of SR and MRR. Babu et al. [8] examined the impact of various variables of EDM. Such as (current, pulse-on-time, and gap voltage) on the following responses (SR, MRR, and HAZ). The experiments were carried out on EN-31 die steel material, whereas copper and brass were used as electrodes material. The obtained outcomes of experiments indicate that the s (HAZ) determined by conduction and cooling action, the available amount of heat during the EDM process.

Shabgard et al. [9], the experiments that have been carried out with different values of the independent variables were pulse duration peak current in electrical discharge machining (EDM) on the HAZ. The copper was used as the electrode material for machining AISI H13 with a cylindrical shape. The authors believe that the lowest depth of heat affected zone on the surface of EDM machined surface can be obtained at the high pulse-current and low pulse–on-time. Choudhry et al. [10] investigated the influence of machining parameters on the heat-affected zone (HAZ) in EDM. Four processes parameters, namely peak current, gap voltage, pulse on time, and electrode materials, have been considered. It was concluded that in the case of the graphite electrode (HAZ) is much deeper as compared to copper and brass electrode. Boujelbene et al. [11] performed a series of experiments on the following materials Steel 50CrV4 and X200Cr15 and comparison between them to find out the effect of process parameters (peak current, pulse discharge, and electrode materials) on white layer thickness and microhardness. The authors believe that the depth of HAZ can be minimized at lower pulse duration and discharge current. From the already stated study, it has been identified that there are few studies concentrated on the distilled water as a dielectric medium in EDM. The Aims of this study are to regression, statistical, and parametric analysis of the influence of process parameters on the HAZ.

2. Experimental Procedure

In the presented research, tool steel (A2) was used as a work-piece. In Table 1, the chemical composition of that work-piece will be listed. The dimensions of the workpiece have been (3.5x38x38) mm and the shape of the workpiece has been square, while for EDM and ECM machining processes, the electrode material has been copper, it is a (60) mm length, and (10) mm diameter. The distilled water has been utilized as the dielectric medium.

EDM machine (CHMER EDM) utilized for the purpose as illustrated in Figure 1 for performing the experiments that are found at the workshop and training center in Iraq - University of technology. RSM was used for designing experiments; matrices were generated depending on the FCCCD, which is the abbreviation of Face-Centered Central Composite Design. Machining parameters, as displayed in Table 2.

Table 1: Chemical composition of the A2-Tool Steel

Element	C	Mn	P	Cr	V	Mo	Si	Fe
Weight%	1	0.6	0.03	5	0.35	1.1	0.3	balance

Figure 1: EDM machine (CHMER EDM)

Table 2: EDM controllable parameters

	Level (1)	Level (2)	Level (3)
Current (A)	30	36	42
Pulse-on Time (µs)	100	150	200
Pulse-off Time (µs)	50	75	100

3. Results

Some experiments were carried out for examining the impacts of input variable parameters on the responses of the process for determining thermal impacts, such experiments have been implemented at the depth of cut = 1mm. The machining characteristics valued for HAZ and made the comparison between observed and predicted data are tabulated in Table 3.

Regression analysis was implemented for determining the relation between the machining process response and input variable parameters. The mathematical model has been created according to experimental data; RSM has been utilized for developing the general 2nd-order model that was applied in the presented research. The mathematical model for various required measures of performance has been created, as shown in equation1.

In order to evaluate the accuracy of this equation, the percentage of error has been measured. The percentage of error represents the difference between predicted and observed value divided by the observed value for all responses. As a result, the prediction accuracy of the developed model has appeared acceptable.

All the terms in the first-order model have been included in the second-order model includes, plus all cross- products terms, all quadratic terms. It is usually expressed as-

$$\mathbf{Y} = \beta_\circ + \sum_{j=1}^{q} \beta_j x_j + \sum_{i=1}^{q} \beta_{jj} x_j^2 + \sum\sum \beta_{ij} x_i x_j + \varepsilon \quad (1)$$

$$= \beta_\circ + x_i^{'} \beta + x_i^{'} \beta x_i + \varepsilon_{ij} \quad (2)$$

Where $\mathbf{x_i} = (x_{1i}, x_{2i}, \ldots, x_{iq})$, $\beta = (\beta_1, \beta_2, .., \beta_q)$

HAZ = 42.7 +0.09 current -0.270 pulse on – 0.006 pulse off + 0.0574 current^2 +0.001567 pulse on^2 +0.00219 $pulse\ off^2$ – 0.00787 current x pulse on -0.01175 current x pulse off -0.000350 pulse on x pulse off (3).

Where N represents the total experimental number, m indicates the number of factors. m_c can be characterized, as 2^m, which indicates cube points at a unit cube corner. m_r can be characterized as 2m, meaning the number of axial or star points along axes. m_o is the experimental central points in the case where all the elements are chosen as 0 level. Peak current (I_P), pulse-on time (T_{on}) and pulse off time (T_{off}) were selected as independent variables in this study, therefore, m=3 in this study, 2^3cube points, 6 axial points, and 6 center points totally 20 experiments have been carried out.

N=m_c+ m_r+ m_o

The quality of the fit for 2nd-order model of regression has been created, also it could be evaluated through coefficient of determination (R^2). Table 4 show (R^2) value, adjusted coefficient of dtermination (R^2_{adj}) for a mathematical model that has been developed. The difference between experimental and predicted data illustrated in Table 3.

ANOVA method was used for determining the prompting factors and to check the efficiency of the 2nd-order model for all the responses of the process of machining. ANOVA has been utilized to test observed values at the confidence level, which is equal to (95) percent. Fisher's statistical test (F-test) was utilized for testing the significance of parameters, the more significant factor is represented via higher (F-test) value. In the case when the p-value ≤ 0.05, it is determined that the factor is of a statistically significant impact. Table 5 shows ANOVA for HAZ.

As illustrated in Figure 2, the main effects of controllable input parameters on a depth of heat affected zone (HAZ), the I_p,T_{on}, and T_{off} have the dominating influence on HAZ; the discharge current is the most significant factor between all the process variables parameters as shown in Figure 3. In addition, HAZ directly proportional to the current, the most prompting factor was current 67.219% contribution exhibit the slightly increased in the mean of HAZ of (7.31), when current rises from first to the second level, whereas shows sharply increased of (18.69), when current rises from second to third. This is explained by the phenomenon that the depth of the thermal effects is directly proportional to the intensity of spark energy when increased in discharge current causes rises in the discharge energy due to which increased the amount of molten metal at high temperature, thereby increased depth of HAZ is produced.

As evident from Figure 2, the relationship between the mean of pulse-on time and mean of HAZ. Exhibit the sharply decreased in the mean of HAZ of (11.9) when pulse-on time rises from (100 μs to 150 μs), whereas shows slightly increased of (0.96), when pulse-on time rises (150 μs to 200 μs). This is because expanded the plasma channel, as mentioned above.

In addition, the mean of HAZ decreases of (9.23) when pulse-off time rates from first to the second level (50 μs to 75μs), whereas the mean of HAZ increased (1.59) when pulse-off time increased from second to the third level (75 μs to 100 μs). The combined influence of process parameters on HAZ as shown in Figure 4.

Table 3: EDM Machining Characteristics Value

RunOrder	Current (A)	Pulse-On(μs)	Pulse-Off(μs)	HAZ		
				Exp.	Pred.	Error %
1	30	150	75	33.5	38.133	-13.829
2	36	200	75	46.4	47.534	-2.443
3	42	150	75	66.6	64.128	3.711
4	36	150	75	49.3	49.069	0.468
5	36	150	100	45.9	46.601	-1.527
6	36	100	75	57.4	58.48	-1.881
7	36	150	50	52.8	54.224	-2.696
8	36	150	75	48.9	49.069	-0.345
9	42	200	50	69.1	67.591	2.183
10	36	150	75	49.5	49.069	0.870
11	42	100	100	73.4	72.105	1.764
12	30	100	50	51.4	48.129	6.363
13	36	150	75	48.4	49.069	-1.382
14	30	200	100	40.9	37.826	7.515
15	42	200	100	53.1	55.554	-4.621
16	42	100	50	80.1	82.391	-2.860
17	36	150	75	49.3	49.069	0.468
18	30	200	50	42.3	42.486	-0.439
19	36	150	75	49.8	49.069	1.467
20	30	100	100	44.2	44.918	-1.6

Table 4: Coefficient Value

	R^2	R^2_{adj}
HAZ	98.11%	95.52%

Table 5: ANOVA for HAZ Response

Source	DF	SS	MS	F-Value	P-Value
Model	11	2466.73	224.25	37.84	0.000
I_p	1	1690.00	1690.00	285.16	0.000
T_{on}	1	299.21	299.21	50.49	0.000
T_{off}	1	145.92	145.92	24.62	0.001
$I_p * I_p$	1	11.48	11.48	1.94	0.202
$T_{on} * T_{on}$	1	41.20	41.20	6.95	0.030
$T_{off} * T_{off}$	1	5.02	5.02	0.85	0.384
$I_p * T_{on}$	1	44.65	44.65	7.53	0.025
$I_p * T_{off}$	1	24.85	24.85	4.19	0.075
$T_{on} * T_{off}$	1	1.53	1.53	0.26	0.625
Residual Error	8	47.41	5.93		
Total	19	2514.15			

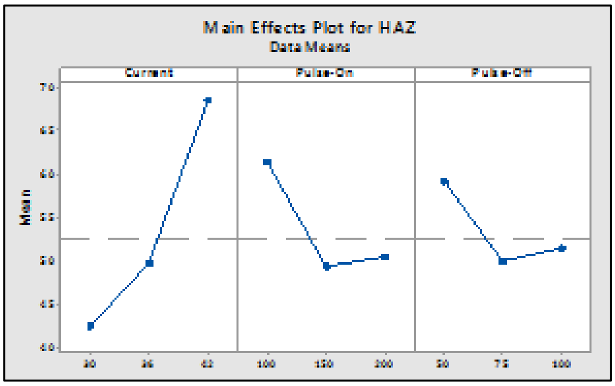

Figure 2: Main effects plot for surface cracks density

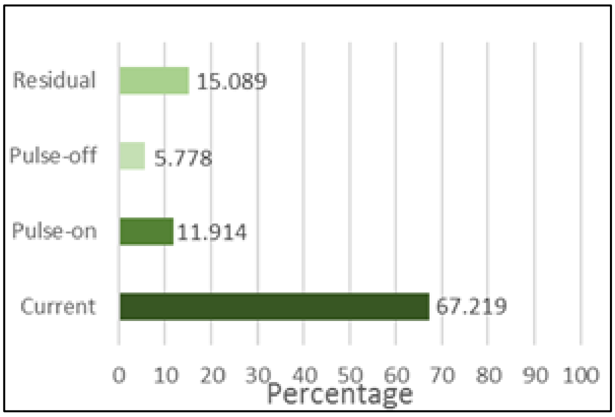

Figure 3: The Percentage Contribution of parameters to HAZ

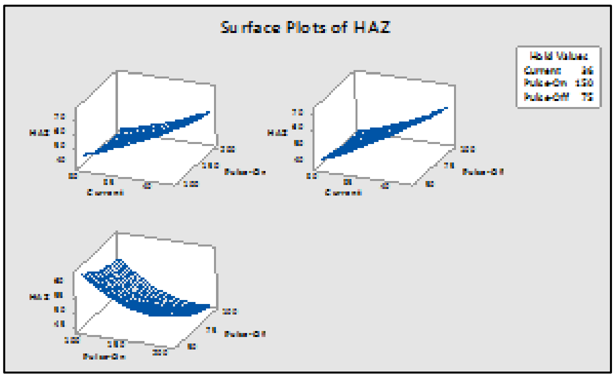

Figure 4: Combination effects of (current, pulse current and pulse-off time) on HAZ

4. Conclusions

The following conclusions are drawn from the experimental results

- The high accuracy of the prediction model was obtained within the experimental data with (-13.829 %) the highest percentage of error.
- From statistical analysis, it can be concluded that the are the most dominating factors affecting HAZ by percentage contribution (67.219%) followed by   with (11.914%), and with (5.778%).

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