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WHITE-LAYER THICKNESS ON EDM-PROCESSED AISI A2 STEEL – MATHEMATICAL MODELING AND ANALYSIS

DEBELINA BELE PLASTI Z EDM POSTOPKOM OBDELANEGA JEKLA AISI A2 – MATEMATIČNO MODELIRANJE IN ANALIZA

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Electrical discharge machining is an electro-thermal technique where the recast layer on a machined surface and the heat-affected zone (HAZ) immediately below the machined surface are prevalent. As a result, assessing the white layer (recast layer) in EDM is a critical task. In this research, a response-surface methodology-based comprehensive mathematical model was developed to predict the white-layer thickness (WLT) on electrical discharge machine-processed AISI A2 steel. Also, the effects of various process parameters on the WLT were presented, the optimum combination of process variables was assessed and the minimum WLT was achieved by combining low-peak current and pulse-on time with high pulse-off time.

Keywords: electrical discharge machining, mathematical model, numerical simulation, response-surface methodology, white layer

Pri postopku obdelave z erozijo (EDM; angl.: Electric Discharge Machining), ki je elektro-termični postopek, nastaja na površini obdelovanca trda pretaljena bela plast in takoj pod njo prehodna toplotno vplivana cona (HAZ; angl.: heat-affected zone). Nastanek bele plasti, ki je posledica taljenja in hitrega strjevanja površine jekla med njegovo EDM obdelavo je kritična točka tega postopka. V tem članku sta opisana raziskava in razvoj odgovarjajočega matematičnega modela, temelječega na metodologiji odgovora površine, za napoved debeline bele plasti (WLT; angl.: white layer thickness) nastale med EDM obdelavo AISI A2 jekla. Prav tako je predstavljena vrsta procesnih parametrov, ki vplivajo na WLT. Podana je ocena optimalne kombinacije procesnih parametrov za nastanek najtanjše WLT s kombiniranjem nizke jakosti vršnega toka in časov vklopa in izklopa tokovnih impulzov.

Ključne besede: mehanska obdelava z erozijo, matematični model, numerična simulacija, metodologija odgovora površine, bela plast

1 INTRODUCTION

Electrical discharge machining is one of the non-conventional machining processes and is a well-known technique for the production of complicated three-dimensional profiles, especially in the die and mould manufacturing industries.[1] It is a thermal machining process where a discharge channel generates thermal energy. The generated thermal energy in the channel causes the melting of the workpiece and evaporation thereof. High-density thermal-energy discharge generates high temperatures, resulting in thermal erosion, a white layer and micro-cracks on the machined-surface recast layer.[2,3] This thermally impacted layer has a distinct structure, different from the parent material and, although it has an advantageous effect as regards better abrasion and erosion resistance, its faults, such as vacuums and breakages, are caused by the stress.[4]

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The thickness of the white layer (WLT) on a processed workpiece significantly influences the surface quality of the specimen. The modification in the thickness of the white layer is crucial for the enhancement of EDM-based research.[5] The prediction of performance indicators in relation to key process variables can result in the creation of a more reliable empirical model of any process.[6] As machining process variables in EDM control the thickness of the recast layer, the WLT may be predicted using EDM process parameters.

The selection of dielectric fluid can have a significant influence on the WLT when machining a nickel alloy with EDM.[7] Adjusting the discharge voltage and pulse-on and -off time in EDM can change the thickness of the recast layer.[8] The modification in the WEDM operation can enhance the machining mechanism that reduces the sample recast-layer thickness.[9] Plasma energy might reduce the thickness of the recast layer in the EDM process under a diluted insulating medium.[10] The distribution of the recast-layer thickness can affect the durability of EDM-machined aeronautical alloys. The process-mechanism efficiency may be increased with the modelling and evaluation of the recast-layer thickness.[11] An analysis of the WLT can enable us to determine the process parameter combinations to improve the surface quality of EDM.[12] Previous research findings show that the current and the pulse-on time are two EDM process variables that have a major influence on the EDM surface integrity.[13,14]

Although numerous research studies on predicting performance indicators for EDM have been conducted, limited attention has been paid to the prediction of the white-layer thickness in the case of electrical-process variables and the influence of machining-process variables on the WLT of machined specimens using EDM.[1–22] The present study attempted to introduce a mathematical model based on the response-surface methodology to predict the WLT on machined AISI A2 steel and investigate the impact of process variables on the WLT.

2 MATERIALS AND METHODS

2.1 Machine, tool and workpiece material

With regard to the current objectives of the research, experimental research and analysis were undertaken to find effective parametric combinations for various cases. The experimental strategy was developed in such a way that the study objectives can be met adequately. The working material was the standard AISI A2 die steel with a composition shown in **Table 1**. At room temperature, each sample was (50 × 40 × 10) mm in size and had a density of 7.750 g/cm^3, a thermal conductivity of 26 W/(m·°C) and a compressive strength of 2200 N/mm^2. An electrolytic copper tool with a 99.9 % purity and a diameter of 10 mm was chosen for machining AISI A2 steel workpiece samples to a depth of one millimetre to examine the effects of various EDM-process variables on the white-layer thickness. The melting point of this copper tool is 1360 K, its electrical resistivity is 17.1 Ωm, its thermal conductivity is 226 W/(m·K) and its density is 8.94 g/cm^3. Commercial graded hydrocarbon EDM oil was chosen as the dielectric fluid because of its high dielectric strength, flash point, transparency and low specific gravity and viscosity. The machining was executed on a CNC EDM machine manufactured by VEE KAY Industries, India.

Table 1: Composition of the AISI A2 steel workpiece

Elements	C	Si	Mn	Cr	Mo	V	Fe
w/%	1.0	0.3	0.6	5.3	1.1	0.2	91.5

2.2 Experimental procedure

The experiments were conducted within a central composite design, with four variables, 16 cubes, 8 axial points and 6 central points, used for a total of 30 runs in 3 blocks. The influential EDM process variables included the discharge current, discharge voltage, pulse-on time, pulse-off time, duty factor, fluid dielectric strength, discharge area and workpiece polarity. Among them, four process variables, each with three levels, were scrutinized and the results are presented in **Table 2**. Machining was performed on AISI A2 steel workpiece samples aiming to remove the material by about one millimetre from the top surface.

Table 2: Machining process variables with their levels

Parameters	Unit	Levels		
		1	2	3
		–1	0	+1
Discharge current	I_p/A	3	6	9
Duty factor	η/%	70	80	90
Pulse-on time	T_{on}/μs	100	200	300
Discharge voltage	U/V	40	50	60

2.3 Measurement of response

After the EDM process, the workpieces were split transversely, polished and etched with three-percent Nital reagent. The sectioned workpieces were then scanned using a Zeiss Gemini FE-SEM scanning electron microscope (SEM), made by Carl Zeiss, for the evaluation of the WLT. The average thickness of the white layer in micrometers (μm) was obtained after taking six SEM micrographs per sectioned workpiece at a magnification of 500× as follows:

$$\text{White-layer thickness} = \frac{\text{Area of the white layer in a SEM micrograph}}{\text{Lenth of the photo of a SEM micrograph}} \quad (1)$$

2.4 Planning based on the response-surface methodology (RSM)

The response-surface methodology includes a collection of mathematical and statistical techniques that are capable of modelling and analysing problems where a response of interest is affected by numerous variables and the purpose is to identify the relationship between the response of interest and the variables under consideration, and optimize this response. When the response function is unknown or nonlinear, a second-order polynomial response-surface mathematical model is generally used. The experimental results are analysed and the mathematical model illustrating the relationship between the process parameters and the response of interest is constructed. As mentioned below, this model is taken into account when determining the parametric impacts on the response criteria (Equation (2)).

$$Y = b_0 + \sum_{i=0}^{4} b_i X_i + \sum_{i=0}^{4} b_{ii} X_i^2 + \sum_{i,j=1,i\neq j}^{4} b_{ij} X_i X_j + \varepsilon \quad (2)$$

Here, Y is the response of interest, i.e., the white-layer thickness; the machining input variables include discharge current (I_p), duty factor (η), pulse-on time (T_{on}) and discharge voltage (U). X_{ii}^2 are the machining in-

Table 3: Different parametric-variable combinations with experimental result

Run order	Pt. type	Block	Coded variable				Machining process parameters				Response WLT/µm
			X_1	X_2	X_3	X_4	I_p/A	η/%	T_{on}/µs	U/V	
1	1	2	1	1	1	1	9	90	300	60	46.72
2	1	2	1	–1	1	–1	9	70	300	40	33.51
3	1	2	–1	1	–1	1	3	90	100	60	20.03
4	1	2	1	–1	–1	1	9	70	100	60	27.08
5	1	2	1	1	–1	–1	9	90	100	40	34.71
6	1	2	–1	–1	–1	–1	3	70	100	40	8.92
7	0	2	0	0	0	0	6	80	200	50	28.61
8	0	2	0	0	0	0	6	80	200	50	28.61
9	1	2	–1	–1	1	1	3	70	300	60	19.59
10	1	2	–1	1	1	–1	3	90	300	40	25.47
11	0	3	0	0	0	0	6	80	200	50	33.71
12	0	3	0	0	0	0	6	80	200	50	28.65
13	–1	3	0	0	0	1	6	80	200	60	29.51
14	–1	3	0	0	1	0	6	80	300	50	31.37
15	–1	3	0	0	–1	0	6	80	100	50	23.61
16	–1	3	–1	0	0	0	9	80	200	50	42.71
17	–1	3	0	0	0	–1	6	80	200	40	30.87
18	–1	3	0	1	0	0	6	90	200	50	34.15
19	–1	3	1	0	0	0	9	80	200	50	42.84
20	–1	3	0	–1	0	0	6	70	200	50	27.79
21	1	1	1	1	–1	1	9	90	100	60	33.74
22	1	1	1	1	1	–1	9	90	300	40	41.27
23	1	1	–1	–1	–1	1	3	70	100	60	11.27
24	0	1	0	0	0	0	6	80	200	50	28.19
25	0	1	0	0	0	0	6	80	200	50	28.45
26	1	1	–1	–1	1	–1	3	70	300	40	19.23
27	1	1	1	–1	–1	–1	9	70	100	40	21.49
28	1	1	–1	1	–1	–1	3	90	100	40	21.41
29	1	1	–1	1	1	1	3	90	300	60	27.35
30	1	1	1	–1	1	1	9	70	300	60	39.76

put-variable square terms, indicating their interaction terms. The unknown coefficients of regression are b_0, b_i, b_{ii}, and b_{ij}. The error of the model is shown as ε.

The second term beneath the summation symbol of the polynomial in Equation (2) corresponds to linear effects, the third term to higher-order effects, and the fourth term to the interactive impact of the process variables. In the RSM technique, each process variable denoted by X is coded in such a way that the upper level of the process variable is recognized as +1 and the lower level as –1. **Table 2** displays the actual and coded parametric values. The number of necessary experiments might be reduced significantly with a well-designed experimental technique. An experimental design was created to determine the WLT equation by employing the lowest number of experiments possible. In light of the present study objectives, the RSM technique was employed to build the mathematical relation between the response Y, i.e., the average thickness of the white layer, and the predominant machining parameters.

3 RSM-BASED MODEL DEVELOPMENT

After determining the average white-layer-thickness values, the values of various coefficients of regression from Equation (2) were calculated and RSM-based mathematical models were created utilising experimental results of the average WLT obtained from the entire set of experiments using computer software called MINITAB.

The effects of different process variables on the thickness of the white layer (Y) were evaluated on the basis of Equation (2) by calculating the values of different Equation constants using the corresponding experimental data from **Table 3**.

Table 4: R^2 and R^2_{adj} test of the mathematical model for WLT

Model's degree	R^2/%	R^2_{adj}/%
linear	93.60	89.70
linear + square	95.50	91.80
linear + interaction	93.80	88.80
full quadratic	97.12	94.44

To determine the regression model's degree, the coefficient of determination (R^2) and adjusted R^2 – statistic values (R^2_{adj}) for various models are compared and reported in **Table 4**. Among the models listed in **Table 4**, the full quadratic model is the best, with R^2 = 97.12 %, showing that the model's predictors or factors explain 97.12 % of the total variation in the response. On the other hand, R^2_{adj} is 94.44 %, which reflects the number of the model's predictors and describes the relationship significance. As a result, for further study in this research, the full quadratic model is taken into account.

Table 5a: Regression coefficients with significance

Term	Coef.	SE coef.	t-value	p-value
Constant	30.547	0.648	47.16	0.000
I_p	7.960	0.514	15.50	0.000
η	4.234	0.488	8.67	0.000
T_{on}	4.556	0.488	9.33	0.000
U	1.009	0.488	2.07	0.056*
$I_p \times I_p$	3.09	1.34	2.31	0.051*
$\eta \times \eta$	–0.75	1.30	–0.58	0.570*
$T_{on} \times T_{on}$	–4.23	1.30	–3.27	0.005
$U \times U$	–1.53	1.30	–1.18	0.255*
$I_p \times \eta$	–0.041	0.518	–0.08	0.939*
$I_p \times \eta$	0.889	0.518	1.72	0.107*
$I_p \times \eta$	0.819	0.518	1.58	0.135*
$\eta \times T_{on}$	–0.776	0.518	–1.50	0.155*
$\eta \times U$	–0.598	0.518	–1.15	0.266*
$T_{on} \times U$	0.522	0.518	1.01	0.330*
S = 2.07221	R^2 = 97.12 %		R^2_{adj} = 94.44 %	

Table 5a displays the regression coefficients in coded units as well as their significance in the regression model. The table's columns related to the terms, coefficient values (Coef.), standard error of the coefficient (SE coef.), t-statistic and p-value are used to assess whether the null hypothesis should be rejected or not. In order to assess the adequacy of the model with a confidence level of 95 %, the p-value of the statistically significant term should be less than 0.05. The terms marked with "*" in the table's last column exceed the 0.05 threshold. As a result, these terms are insignificant and should be dropped from further consideration. The backward elimination process rejects the insignificant variables and adjusts the quadratic model. **Table 5b** shows the model with the remaining terms after the elimination when the R^2 and R^2_{adj} values are 93.6 % and 91.3 %, respectively. The simplified model has lower R^2 and R^2_{adj} values, showing that the relationship between the response and the machining process variables is significant. Post-elimination significant terms of the truncated model are I_p, T_{on}, η, T^2_{on}.

The final mathematical relation for correlating the average WLT with the machining process variables is as follows:

$$\mathrm{WLT} = -144.5 - 3.32\, I_p + 2.09\, \eta + 0.2331\, T_{on} - 0.000423\, T_{on} \times T_{on} \quad (3)$$

This mathematical model can be used to examine the influence of process variables on the WLT in the EDM process when machining the AISI A2 steel material.

Table 5b: Regression coefficients with significance (post backward elimination)

Term	Coef.	SE coef.	t-value	p-value
Constant	30.547	0.648	47.16	0.000
I_p	7.960	0.514	15.50	0.000
η	4.234	0.488	8.67	0.000
T_{on}	4.556	0.488	9.33	0.000
$T_{on} \times T_{on}$	–4.23	1.30	–3.27	0.005
S = 2.07221	R^2 = 93.6 %		R^2_{adj} = 91.3 %	

The analysis of variance (ANOVA) was used to investigate the appropriateness of the second-order model that contains tests on the regression model significance, model coefficients and lack-of-fit. **Table 6** summarizes the model's ANOVA, which includes two sources of variation: regression and residual error. The variance caused by model terms is the combination of linear and square terms, while residual error is caused by pure error and lack-of-fit. The table columns show sources of variation, degree of freedom as DF, adjusted sum square error as Adj SS, adjusted mean square error as Adj MS, f-values and p-values. The p-value for lack-of-fit is 0.418, which shows that the lack-of-fit is statistically insignificant at the 95-percent confidence level. Furthermore, the p-value for all the linear variables in the model is 0.000, and the p-value for square variables is 0.003, indicating that they are statistically significant at the 95-percent confidence level and that the regression model accurately represents the experimental data.

Table 6: Analysis of variance (ANOVA)

Source	DF	Adj SS	Adj MS	f-value	p-value
Regression model	4	2175.71	155.41	36.19	0.000
Linear	3	1746.27	436.57	101.67	0.000
Square	1	115.95	28.99	6.75	0.003
Error	15	64.41	4.29	–	–
Lack-of-fit	9	41.65	4.63	1.22	0.418*
Pure error	6	22.76	3.79	–	–
Total	19	2240.12	–	–	–

Hence, the established mathematical models that correlate various machining process variables with the WLT may adequately describe EDM operations using the response-surface methodology.

4 RESULTS AND DISCUSSION

The effects of four predominant machining process variables in EDM on the WLT were investigated using a nonlinear mathematical model constructed with the RSM technique. Other fixed parameters such as fluid dielectric strength, discharge area, workpiece polarity and flushing pressure remained constant during the electrical-discharge machining of a standard AISI A2 steel workpiece specimen.

4.1 Adequacy of the mathematical model

The analysis of variance (ANOVA) was used to validate the adequacy of the developed mathematical models. At a 93.6 % confidence level, the second-order regression models with four degrees of freedom are acceptable for expressing the relationships between the WLT and EDM machining process variables. Hence, the established regression model that relates various machining process variables with the WLT adequately represents the relationship using the RSM technique for an EDM operation.

The fitted model provides estimated responses, whereas residuals are calculated from the difference between the fitted and experimental values. **Table 7** shows the machining process variables for every run order as well as the experimental findings (Exp.), estimated model predictions (Pred.) and residues (Resi.) where the residues indicate the gap between experimental findings and estimated model predictions. The estimated model predictions for the WLT obtained using Equation (3) are

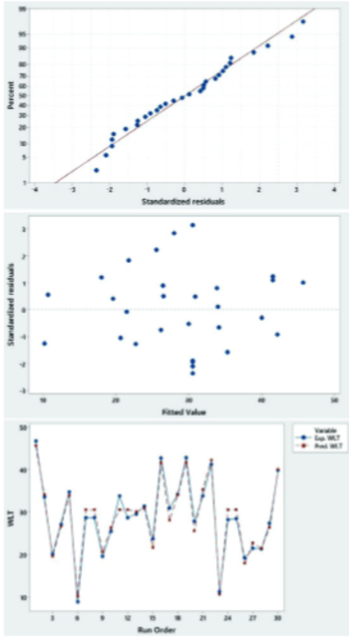

Figure 1: Plots showing the adequacy of the mathematical model: a) normal probability plot of standardized residuals, b) standardised residuals versus fitted value, c) predicted vs. experimental results for WLT in μm

Table 7: Comparison of experimental and prediction results of regression model

Run order	Machining process parameters				WLT/μm		
	I_p/A	η/%	T_{on}/μs	U/V	Exp.	Pred.	Resi.
1	9	90	300	60	46.72	45.69	1.03
2	9	70	300	40	33.51	34.16	–0.65
3	3	90	300	60	20.03	19.61	0.42
4	9	70	100	60	37.08	26.57	0.51
5	9	90	100	40	34.71	33.89	0.82
6	3	70	100	40	8.92	10.18	–1.26
7	6	80	200	50	28.61	30.55	–1.94
8	6	80	200	50	28.61	30.55	–1.94
9	3	70	300	60	19.59	20.64	–1.05
10	3	90	300	40	25.47	26.21	–0.74
11	6	80	200	50	33.71	30.55	3.16
12	6	80	200	50	28.65	30.55	–1.90
13	6	80	200	60	29.51	30.02	–0.51
14	6	80	300	50	31.37	30.87	0.50
15	6	80	100	50	23.61	21.76	1.85
16	9	80	200	50	42.71	41.60	1.11
17	6	80	200	40	30.87	28.00	2.87
18	6	90	200	50	34.15	34.03	0.12
19	9	80	200	50	42.84	41.60	1.24
20	6	70	200	50	27.79	25.56	2.23
21	9	90	100	60	33.47	35.31	–1.57
22	9	90	300	40	41.27	42.19	–0.92
23	3	70	100	60	11.27	10.71	0.56
24	6	80	200	50	28.19	30.55	–2.36
25	6	80	200	50	28.45	30.55	–2.10
26	3	70	300	40	19.23	18.02	1.21
27	9	70	100	40	21.49	22.76	–1.27
28	3	90	100	40	21.41	21.47	–0.06
29	3	90	300	60	27.35	26.44	0.91
30	9	70	300	60	39.76	40.06	–0.30

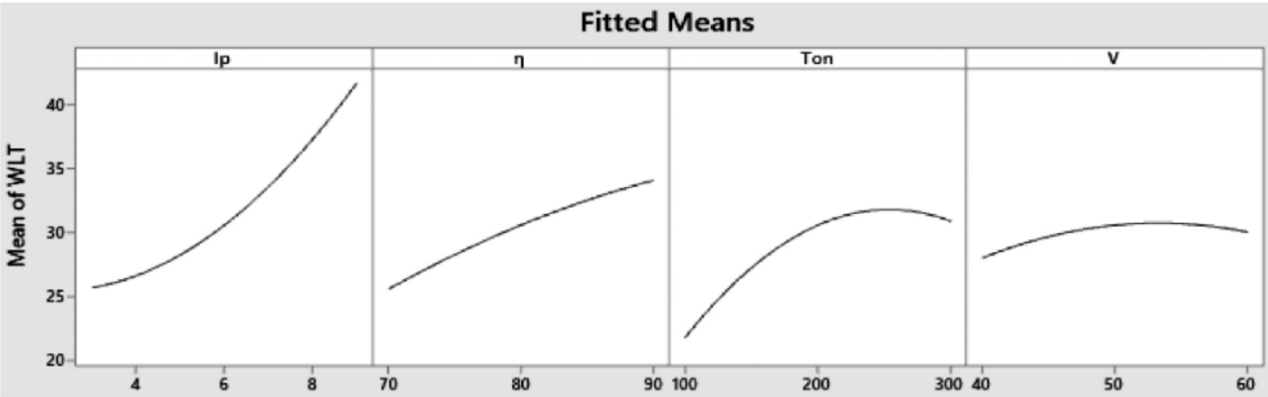

Figure 2: Main effects plot for WLT

close to the observed values, demonstrating the model's adequacy.

In **Figure 1a**, standardized residuals are shown in the normal probability plot to analyse the data deviation from normality. Residues are nearly in a straight line, indicating that they are distributed normally and the assumption of normality is valid. Furthermore, in **Figure 1b**, the plot of the residues against the run order reveals that the data lacks any set pattern or unique structure. The residues, ranging from –2.36 to 3.16, are distributed randomly around zero, suggesting that the deviations have a constant variance. Plots of residues are an essential addition to regression-model computations, and may be compiled against the fitted data to visually examine the assumptions of the model. In **Figure 3c**, experimental findings are analogized to estimated model-prediction values. Hence, the regression model may be seen to be reasonably well matched with the experimental results.

4.2 Analysis of parametric influences on the WLT

The white layer created as a result of the re-solidification of the molten material due to inadequate cooling during the electrical discharge machining was carefully investigated for various combinations of process parameters. The WLT and HAZ are affected by heat transmission and changes in the microstructure of the workpiece during the EDM process. It is anticipated that a white layer will form on the EDMed surface, which can be regulated with the effectiveness of heat transfer by quickly solidifying the molten metal. The transfer of heat depends on the quantity of heat supplied by pulse energy.

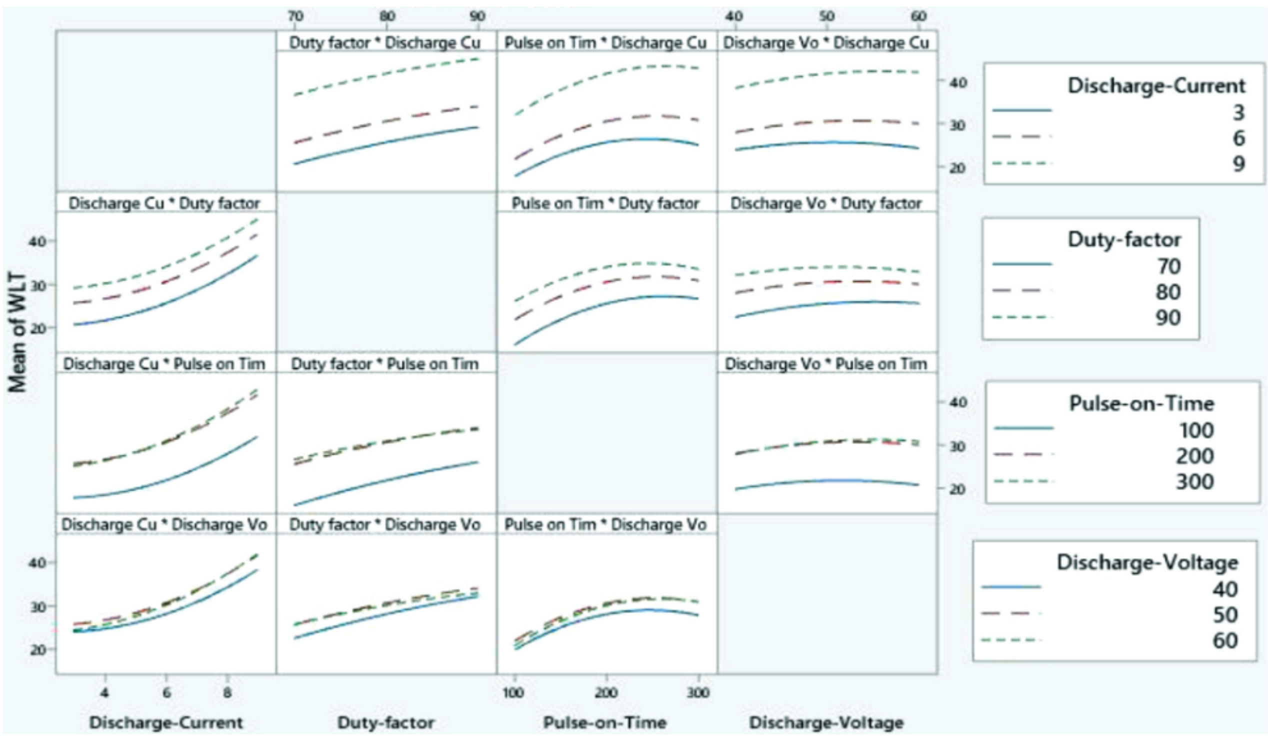

Figure 3: Interaction plot for WLT

During the process, the heat transfer depends on the spark energy provided. That is why discharge current I_p and the duration of T_{on} and T_{off} are the key parameters. The depth and size of the craters generated by the spark are determined by the pulse current and pulse duration. In other words, if I_p and T_{on} are lowered, only a small amount of spark energy is provided, resulting in the creation of minor craters and reduced heat, which reduces the recast-layer thickness and HAZ. Furthermore, if T_{off} is higher, which is the interval between the termination of one spark and the beginning of another, the workpiece will be able to distribute heat and therefore reduce the recast-layer thickness.

The influence of discharge current on the WLT during EDM of a workpiece of die steel was analysed based on the established nonlinear mathematical model, i.e., Equation (3). **Figure 2** shows how the WLT increases with the rise in the discharge current. This may be explained by the fact that there is a constant amount of molten metal that the dielectric can flood away. As the maximum current increases, more heat is transmitted to the sample and the dielectric is increasingly unable to remove the molten material, which, as a result, accumulates on the parent material's surface. During the subsequent cooling, the molten material re-solidifies to create the recast layer, the thickness of which is governed by the amount of the molten material.

Figure 4 may be used to examine graphically the influence of the process variables on the response. According to the results presented in **Table 6**, I_p, T_{on}, and η have significant impacts on the WLT. Among them, I_p is the most significant and influential process parameter; when it rises from 3 A to 6 A and 6 A to 9 A, the average WLT grows by 5.29 μm and 10.75 μm, respectively. On the

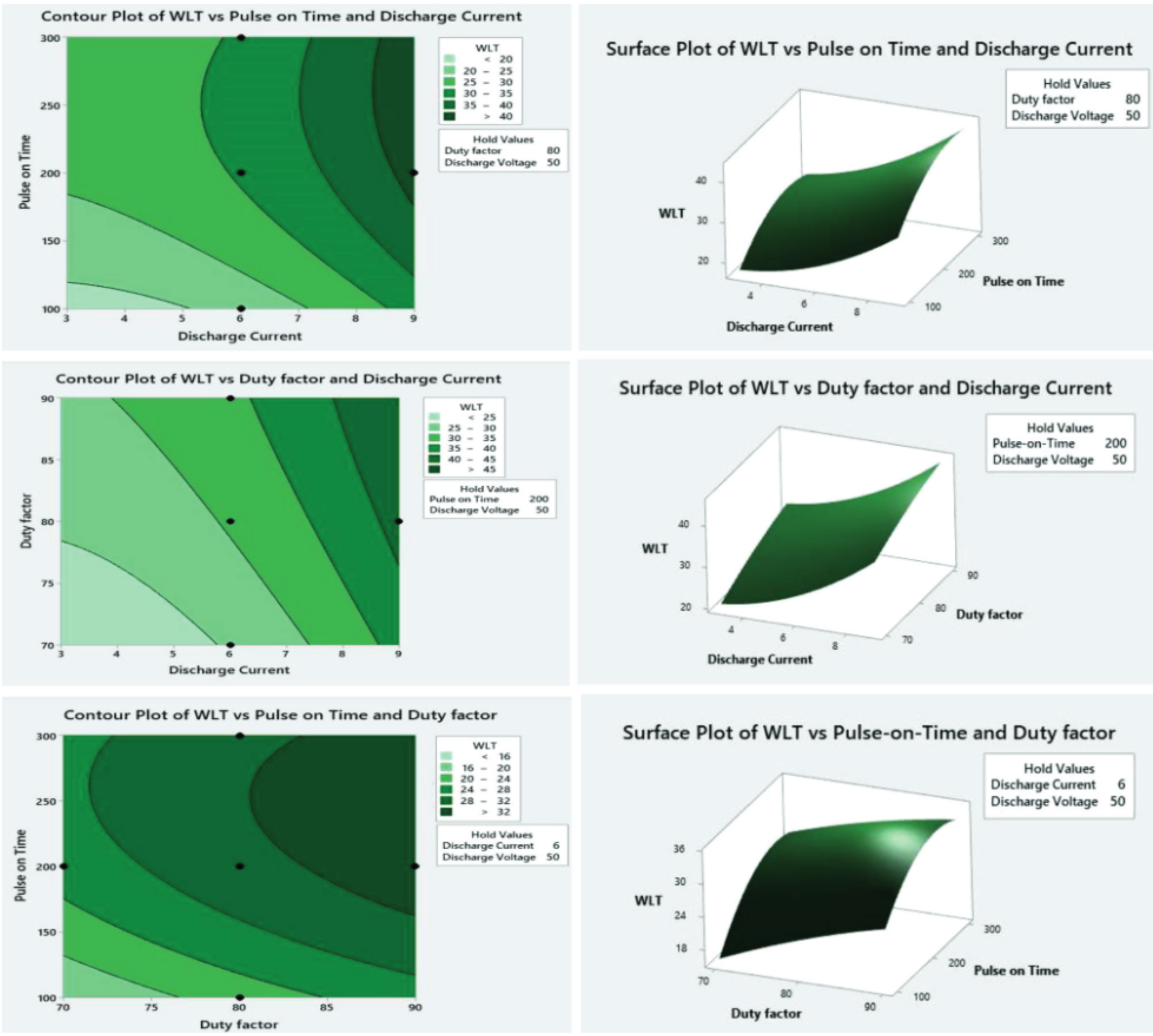

Figure 4: Contour and response-surface plot of WLT: a) I_p and T_{on} (contour plot), b) I_p and T_{on} (response-surface plot), c) I_p and η (contour plot), d) I_p and η (response-surface plot), e) T_{on} and η (contour plot), f) T_{on} and η (response-surface plot)

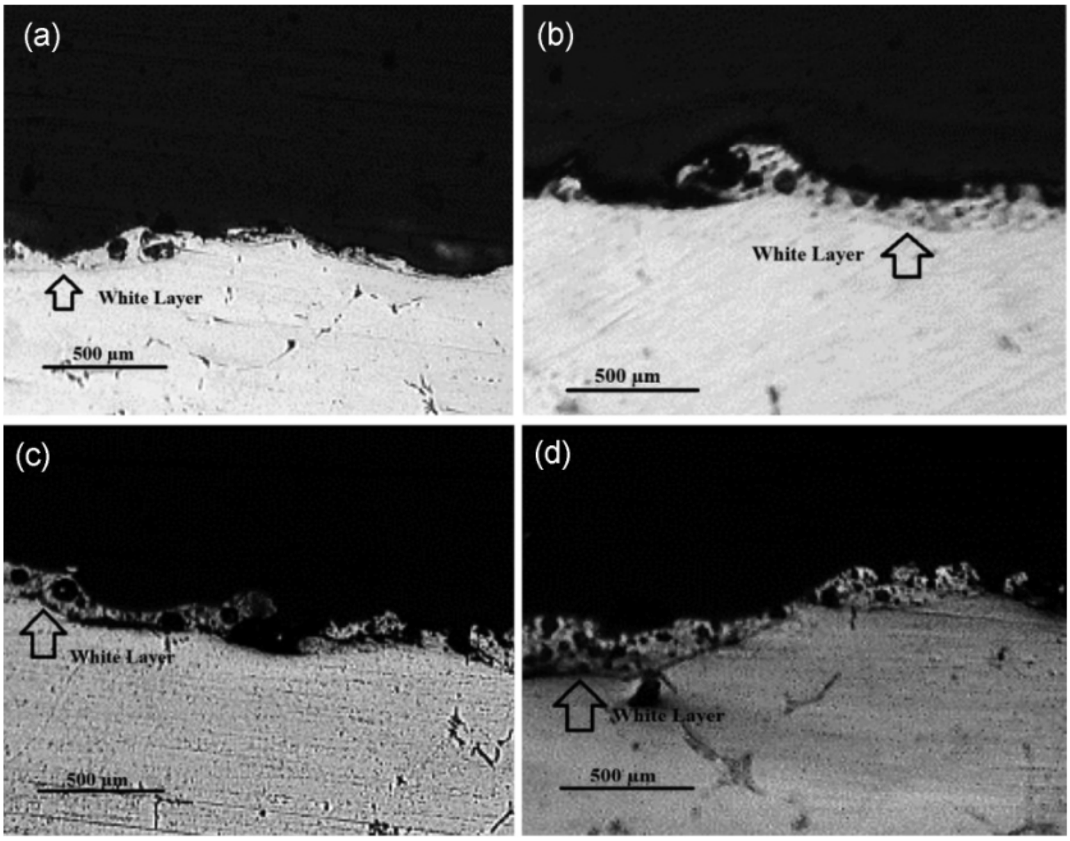

Figure 5: SEM micrographs at: a) 3 A, 80 %, 200 µs, 50 V, b) 6 A, 80 %, 200 µs, 50 V, c) 9 A, 80 %, 200 µs, 50 V, d) 9 A, 90 %, 300 µs, 60 V

other hand, η is again directly proportionate to the WLT. When η rises from 70 % to 80 % and from 80 % to 90 %, the average WLT grows by 5.24 µm and 3.45 µm, respectively. Furthermore, the WLT is directly proportionate to T_{on} whose primary influence is a sudden increase of 12.65 µm as it goes from 100 µs to 200 µs, followed by a 0.5 µm increase when it increases from 200 µs to 300 µs.

The interaction graphs for 2-variable interactions among I_p, T_{on}, η and U are shown in **Figure 3**. One process-variable pair is shown while the other process variables remain constant at the mean point level. The plot shows interest progress from low to moderate, and then from moderate to high. If the lines in the interaction plot are parallel, there is no interaction between the process variable pairs. If the lines are not parallel, there is interaction among process variable pairs. The greater the deviation from parallelism, the greater is the interaction impact. The interaction plot shows that none of them significantly overlaps, indicating there is no significant interaction at the 95 % confidence level, which is confirmed by **Table 5b.**

Figures 4a and **4b** show the contour graph and response surface for the WLT for I_p and T_{on} machining process variables. The figure shows that for any value of T_{on}, the WLT tends to grow considerably with the rise in I_p. This may be explained with the fact that there is a constant amount of molten metal that the dielectric can flood away. As the maximum current increases, more heat is transmitted to the sample and the dielectric is increasingly unable to remove the molten material, which, as a result, accumulates on the parent material's surface. During the subsequent cooling, the molten material re-solidifies to create a recast layer, the thickness of which is governed by the amount of the molten material. It can also be observed that when T_{on} grows, the WLT increases quickly to a point and then keeps increasing slowly, indicating that T_{on} is a critical regulating variable. In the case of a longer T_{on}, typically, quite intense heat is generated, going deep into the workpiece material and melting more material, therefore producing a deeper white layer following the subsequent quenching. However, after further increasing T_{on}, the heat provided is dispersed into the surrounding environment and the rise in the temperature is comparatively small, resulting in a comparatively modest increase in the volume of the molten workpiece material. Hence, the early gradient is steeper than the later gradient. As a result, the highest WLT is produced at a high discharge current (9 A) and a long pulse-on time (300 µs). To reduce the WLT, I_p and T_{on} should be reduced and the pulse-off time (T_{off}) increased, allowing the heat to escape.

The contour graph and response surface for the WLT are displayed in **Figures 4c** and **4d** showing discharge current I_p and duty factor η, where T_{on} remains constant at its mean level of 200 µs. It should be noticed that as I_p grows, so does the WLT; the reason for this is the same as before; however, as η grows, so does WLT because the duty cycle (η) is the fraction of T_{on} to pulse period (the summation of T_{on} and T_{off}) as in Equation (4). In the case of a fixed T_{on}, the higher the duty cycle, the lower is T_{off} and vice versa. So, in order to reduce the WLT, T_{off} should be high, i.e., η should be as low as feasible, as shown in **Figures 4c** and **4d**.

$$\eta = \frac{T_{on}}{T_{on} + T_{off}} \tag{4}$$

Lastly, **Figures 4c** and **4f** show the WLT as a function of T_{on} and duty factor η, whereas I_p stays constant at 6 A. As seen in the figure, the lowest feasible WLT value occurred with a low T_{on} and small η. Based on these findings, it is possible to conclude that I_p, T_{on} and η are directly proportionate to the WLT for the provided set of experiments for this test.

The SEM micrographs in **Figures 5a** to **5d** were obtained at the parametric combinations of (3 A, 80 %, 200 µs, 50 V), (6 A, 80 %, 200 µs, 50 V), (9 A, 80 %, 200 µs, 50 V) and (9 A, 90 %, 300 µs, 60 V), respectively. These figures show that for any value of T_{on}, the WLT tends to grow considerably with an increase in I_p; the explanation is the same as before. However, **Figure 5d** shows the WLT maximum value at the uppermost values of machining parametric variables.

The WLT of these four SEM micrographs therefore matches with the established mathematical model. The similarities in the curve patterns created by the constructed mathematical model and acquired via experimental data presented in **Figures 2** and **4**, prove the validity of the regression model built for the WLT.

5 CONCLUSIONS

In this work, an attempt was made to introduce the RSM technique to estimate the average white-layer thickness when machining standard AISI A2 steel using the EDM process through 30 different combinations of experimental runs. The RSM-based mathematical model was validated by comparing the experimental and predicted values. It was found that the developed RSM-based mathematical model has a 93.6 % accuracy in predicting the average white-layer thickness.

The test findings show that the discharge current followed by pulse-on time and duty factor have a substantial impact on the white-layer thickness. Furthermore, diverse test findings and experimental analyses confirmed a higher-order influence of the dominant variable, i.e., the peak current on the WLT.

The following findings were obtained from a detailed analysis of the graphs created using established mathematical models of the white-layer thickness and an analysis based on several SEM micrograms:

- In order to minimise the average WLT, the discharge current should be reduced as much as possible, ideally to 3–6 A, and the pulse-on time should be between 100–200 µs because a higher discharge current, i.e., greater than 9 A, will result in a poorly machined surface with a thick white layer.
- For the WLT, the discharge current was found to be the most influential process variable, followed by the pulse-on time. The thickness of the white layer increases with the discharge current (I_p), duty factor (η) and pulse-on time (T_{on}).
- In order to minimise the white-layer thickness, the process variables including the discharge current (I_p), duty factor (η), pulse-on time (T_{on}) and discharge voltage (U) should be kept at their lowest values. The optimum WLT parameter settings were found to be: I_p = 3 A, T_{on} = 100 µs, η = 70 % and U = 40 V.

The study findings in the field of die-steel machining will be beneficial to manufacturing engineers in determining the optimal parametric combinations of the EDM process, using the established mathematical models. Using the current research results to achieve the necessary degree of quality of the EDM-ed surface integrity is a big step towards the objective of achieving highly precise and accurate machining operations with EDM.

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