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Assessment of Recast Layer while Machining Die Steel D3 on EDM

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Abstract: The material melted and quickly solidified on the surface, forming a Recast layer over the machined surface. The present experimental assessment measures the extent of influence of machine variables towards the deposition of recast material post-machining Die Steel D3. The microstructure of the recast layer is dendritic and columnar due to sudden quenching, causing complex phase transformation. Scanning Electron Microscopy is utilized to assess the range of recast deposition. The range of average recast deposition is between 32.7 to 68.5 µm. The sequential model and lack of fit tests depict that the EDM parameters and recast layer can be modeled using 2FI equations. The analysis apprised that peak current (p-value < 0.0001) has a crucial impact on recast deposition. The duration (p-value = 0.4694) was the minimal affecting factor amid selected variables for white layer thickness, which aligns with the previous literature. The impact of current and duration is almost linear towards recast layer thickness and higher deposits of recast layer (RL) are observed at higher levels of current and duration. Lower RL can only be attained by setting a lower current and on duration. The influence of lower voltage is not much on recast layer thickness at minimum value of peak current. The residual error of 3.13% during model validation illustrates the adequacy of the model.

Introduction

Through melting and vaporisation, electro-discharge machining (EDM) removes material from a surface by harnessing the powerful force of sparks that impact the object. The heat generated in the sparking zone is sufficient to remove the material. Since the spark strikes the closest point on the work, even surface with better surface quality is achieved. The process of effective machining is carried out in a dielectric medium. Post-machining, the material is melted, quickly solidifies on the surface, and forms a Recast layer over the machined surface. It is brittle and is subjected to cracking. It has a distinct, separate structure from that of the base metal. The microstructure of the recast layer is dendritic and columnar due to sudden quenching, causing complex phase transformation. The formation of recast is unwanted and numerous studies have been carried out to minimize or avoid solidification of the layer post machining.

Several investigations have been conducted using various work materials to assess the nature of machine variables that affect the deposition of the recast layer. Many investigations have been carried out to optimize the set of EDM variables to reduce the solidification of this recast layer over the machined surface. An investigation for analyzing tool wear and recast layer developed the mathematical model and found that the pulse current was a major influencing factor for tool wear and recast layer. Furthermore, they found that the duty factor was insignificant for the performance measures. Their

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developed model shows that AISI 4340 can be used commercially for industrial applications (Rizvi et al., 2018).

During research with powder-mixed EDM to analyze surface roughness and the rate of material removal, it was found that powder-mixed dielectric fluid enhances the material removal rate and minimizes the machined surface's roughness. It was also concluded that by adding chromium powder, a higher metal removal rate is obtained and rougher surfaces are obtained. An inverse effect is observed when aluminium powder is added (Modi et al. 2019).

In another research for assessing the rate of metal removal, surface roughness, developed residual stresses, and cracks during electro-discharge machining of AISI 4340, it was found that current and duration are the crucial variables for all performance measures. Moreover, surface crack density tends to increase at a lower level of current. A higher duration widens up the rupture. Further, it was concluded that the internal stress developed fluctuates when the induration is varied (Rizvi et al., 2016).

Research on Nimonic 90 with powder-mixed EDM found that powder in dielectric reduces the roughness as well as the recast deposited post-machining. On duration was a crucial parameter for both the responses (Alhodaib et al., 2021).

Another research focused on developing a model to predict recast layer thickness. The developed model had an accuracy of 97% (Muthuramalingam et al., 2019). An investigation conducted on Inconel 825 to assess the crack density and recast layer found that the crack density was majorly dominated by current and duration, while the formation of the recast layer depends only on duration (Kumar et al., 2021).

Moreover, another research conducted to find suitable electrode for machining identified that copper with brass coating produces higher rate of material removal. It was also concluded that copper with brass coating leads to a lower rate of tool wear (Balamurugan et al., 2020).

Another research revealed that the recast layer experiences cracks as it is heterogenous in nature (Ekmekci, 2009). Another investigation also found that the discharge energy directly influences the recast layer thickness. Moreover, they found that on duration was a crucial factor for recast layer formation. Heat source also influences the deposition of the recast layer (Gostomirovic et al., 2012).

One research also found current to be crucial for recast layer thickness. They also revealed that on duration must be minimum for lower recast layer thickness (Rajesha et al., 2014). Furthermore, it was discovered that the recast layer disappears when a powder-suspended dielectric is used (Pecas et al., 2008). While studying the extent of roughness produced during EDM of AISI 4340, all the selected parameters were found to have crucial significance over the response, and the trend followed an increasing trend with all the chosen machine variables (Rizvi et al., 2020).

An investigation used graphite mixed argon gas in place of dielectric and found that the gas pressure influences the machined surface's roughness and the white layer's deposition. White layer deposition is higher at elevated levels of machine variables (Janardhana et al., 2023).

A study assessed the surface quality of AISI 4147 while machining on EDM and concluded that duration is the influential machine parameter. It was also found that machining depth was insignificant for surface quality (Verma et al., 2024). Furthermore, the migration of material of the two electrodes was also observed while machining on EDM. The higher discharge energy makes the composition of the electrode loosen at higher temperatures, thus resulting in the transfer of material from one electrode to another (Rizvi et al., 2023; Jain et al., 2023). The formation of a black layer over the tool surface and its impact on the wear of the tool was also analyzed. The duty factor emerges as the major dominating factor that makes the black layer more distinct and thus reduces the tool's wear rate (Rizvi et al., 2020).

Through the in-depth survey of the above literature, the gap pointed out for the present assessment is to investigate the thickness of recast deposition and to optimize the EDM variables for minimal recast layer thickness (RLT). The literature also shows that current, on-duration, and voltage have majorly influenced the recast layer deposition and hence selected for this research too. Simultaneous optimization of the response is carried out with RSM central composite design to identify an optimal set of machine variables.

Materials and Methods

The present assessment looks forward to establishing a predictive model for the deposited recast layer over the Die Steel D3 workpiece post-machining. The experiments were planned based on Response Surface Methodology. The linear measurement tool of Carl Zeiss Evo 50 SEM machine was utilized to measure the thickness of the deposited recast layer. Figure 1 below depicts the setup of machine for machining the workpiece.

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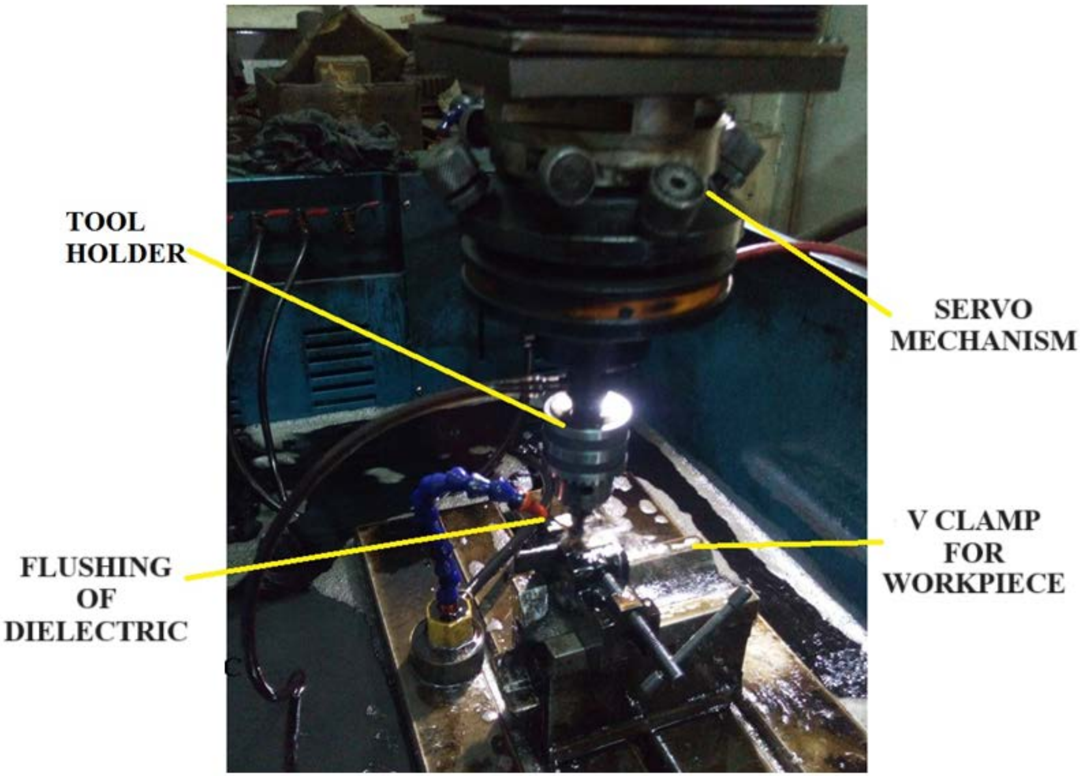

Figure 1. Machine setup for machining Die Steel D3.

Table 1. EDM Parameters and their levels.

Parameters	Current	On Duration	Voltage
Units	A	µsec	V
Level 1	1	10	90
Level 2	5	15	120
Level 3	9	20	150

Table 2. Average Recast Layer thickness for each trail.

Trail No.	Peak Current (A)	Pulse on Time (µ-sec)	Voltage (V)	Recast Layer Thickness 1	Recast Layer Thickness 2	Recast Layer Thickness 3	Average RLT (µm)
1	1	10	90	33.6	28.2	37.8	33.2
2	9	10	90	53.2	83.3	58.8	65.1
3	1	20	90	28.9	22.5	39.8	30.4
4	9	20	90	66.4	69.7	69.4	68.5
5	1	10	150	35.7	38.2	27.8	33.9
6	9	10	150	33.9	35.7	37.8	35.8
7	1	20	150	31.6	34.6	34.9	33.7
8	9	20	150	45.4	42.2	43.2	43.6
9	1	15	120	31.5	35.7	30.9	32.7
10	9	15	120	66.9	61	69.8	65.9
11	5	10	120	32.4	38.2	37.1	35.9
12	5	20	120	42.3	40.2	45.6	42.7
13	5	15	90	38.2	37.4	34.8	36.8
14	5	15	150	40.6	37.6	37.9	38.7
15	5	15	120	48.7	49.6	49.9	49.4
16	5	15	120	49.5	49.1	50.5	49.7
17	5	15	120	51.2	47.5	50.1	49.6
18	5	15	120	49.4	48.6	51.4	49.8
19	5	15	120	49.8	49.6	50.3	49.9
20	5	15	120	48.7	52.2	48.2	49.7

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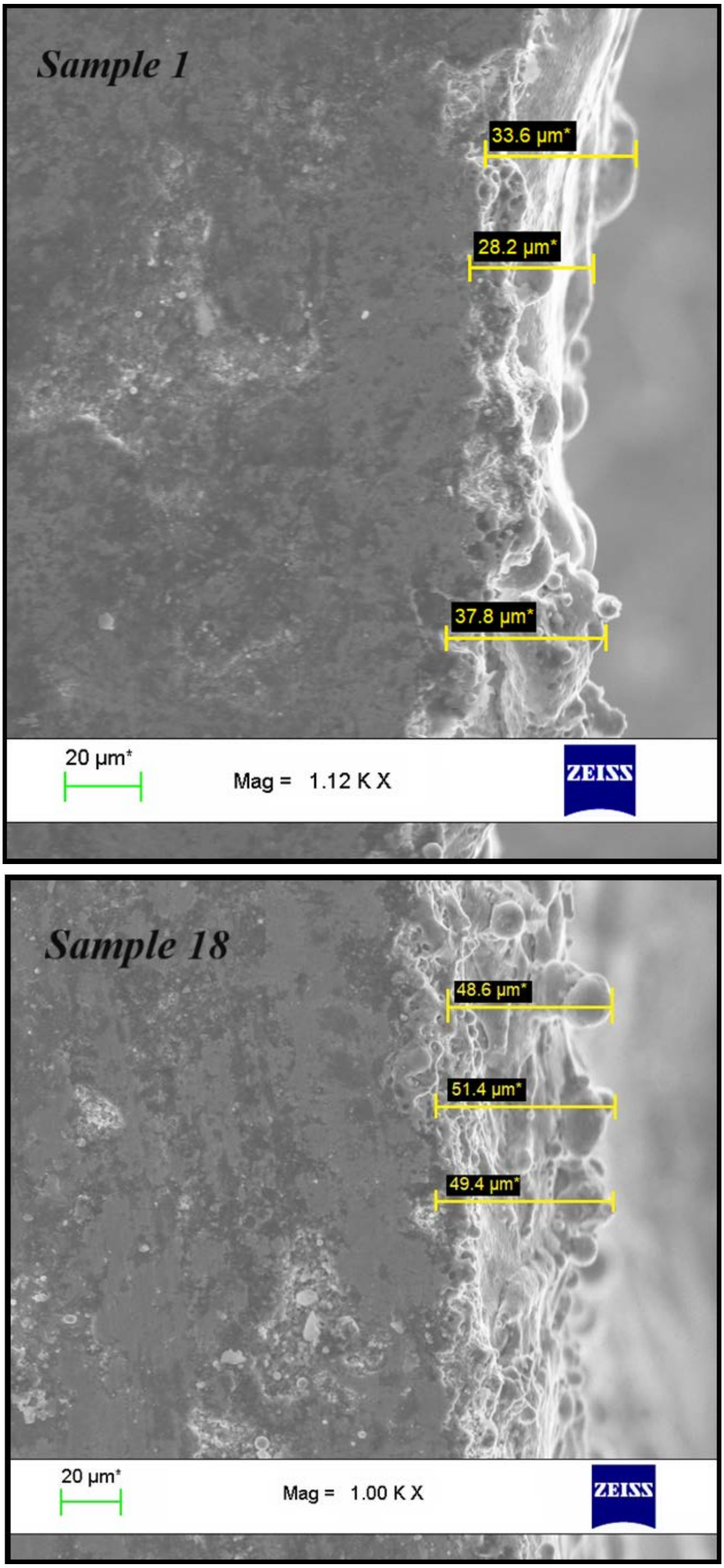

Figure 2. Recast Layer Deposition on Sample 1 and Sample 18 using scanning electron microscopy.

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The EDM variable range was fixed based on performance in the initial trials. As the electrical parameters were kept low, poor sparking was observed. Based on the literature survey, the upper range of the parameters was initially set. With further trials, the final range of all three variables was fixed. Table 1 below depicts the level of EDM variables and Table 2 illustrates the trail list based on RSM, along with the average recast layer thickness for each trail.

The above figure 2 depicts the linear measurements of deposited recast layer over Sample 1 and Sample 18 using scanning electron microscopy. Die Steel D3 is selected as the work material while pure copper is chosen as the tool. It is high carbon and high chromium alloy steel that possesses high abrasion or wear resistance, better dimensional stability, and higher compressive strength. Table 3 shows the chemical composition of Die Steel D3 by weight.

between the recast layer and EDM variables. To find the model type for the trend of recast layer, SMSS and lack of fit tests were performed in Tables 4 and 5, respectively. Both these tests suggested a Two Function Interaction model.

Analysis of Variance for 2FI model was conducted for the recast layer thickness of the machined surface as depicted in Table 6 below. The model F-value = 8.36 indicates the significance of the model. Only 0.07% chances are there that this F-value will occur because of noise. This implies that the data in the model is under 95% confidence interval. The p-value lower than 0.05 shows the significance of model terms. In this model, peak current (A), voltage (C) and peak current-voltage (AC) are crucial variables.

It was found that on duration (p-value = 0.4694) was the minimal affecting factor amid selected variables for recast layer thickness, which is in line with the previous literature (Alhodaib et al., 2021; Kumar et al., 2021; Gostomirovic et al., 2012). Peak current is the major dominating variable (p-value < 0.0001) for the present model, which substantiates the previous research on

Table 3. Chemical constituents of Die Steel D3 by weight.

Material	% Composition
Iron	86.5
Nickle	0.0689
Manganese	0.269
Chromium	11.05
Carbon	2.07
Silicon	0.191
Copper	0.00367
Vanadium	0.0218
Molybdenum	<0.002

Table 4. Sequential Model Sum of Square Test (SMSS) for the present model.

Source	Sum of Square	DOF	Mean Square	F-Value	p-value	
Mean vs Total	40051.25	1	40051.25			
Linear vs Mean	1578.29	3	526.10	8.58	0.0013	
2FI vs Linear	454.73	3	151.58	3.74	0.0389	Suggested
Quadratic vs 2FI	256.35	3	85.45	3.16	0.0729	
Cubic vs Quadratic	157.98	4	39.50	2.11	0.1979	Aliased
Residual	112.44	6	18.74			
Total	42611.04	20	2130.55			

Table 5. Lack of Fit Test for the present model

Source	Sum of Square	DOF	Mean Square	F-value	p-value	
Linear	981.35	11	89.21	3007.21	<0.0001	
2FI	526.62	8	65.83	2218.89	<0.0001	Suggested
Quadratic	270.27	5	54.05	1822.03	<0.0001	
Cubic	112.29	1	112.29	3785.11	<0.0001	Aliased
Pure Error	0.1483	5	0.0297			

Result and Discussion

The values of the recast layer deposited over the machined surface depicted in Table 2 were analyzed to derive the polynomial equation for estimating the relation recast layer thickness (Gostomirovic et al., 2012; Rajesha et al., 2014). The lack of fit F-value of 2218.89 suggested the significance of the lack of fit.

The surface plot for the 2FI response model of recast layer thickness is depicted by Figures 3, 4 and 5. The parameters considered are current with on time in Plot 3, peak current and voltage in 4 while pulse on time and voltage are considered in figure 5, as they are crucial variables for recast layer depicted in ANOVA table. The surface plot 3 shows that the impact of current and on duration is almost linear towards recast layer thickness and higher deposits of recast layer are observed at elevated level of current and on time. Lower RL can only be attained by setting a lower current and duration. From surface plot 4, the insignificance of lower voltage on RLT at the lower level of current can be observed. However, at higher level of peak current, the RL formation decreases with an increase in voltage. The surface plot depicted in figure 5, the curve is almost flat and minimum variation is observed when voltage and duration are considered. A lower voltage and duration are suggested to minimize the recast layer's deposition during EDM of Die Steel D3.

The developed recast layer is the solidified debris removed during the process of machining. This layer will hinder the further machining process to a certain extent, which may influence its effectiveness. Thus, to minimize the deposition of recast, minimum values for the chosen variables must be set.

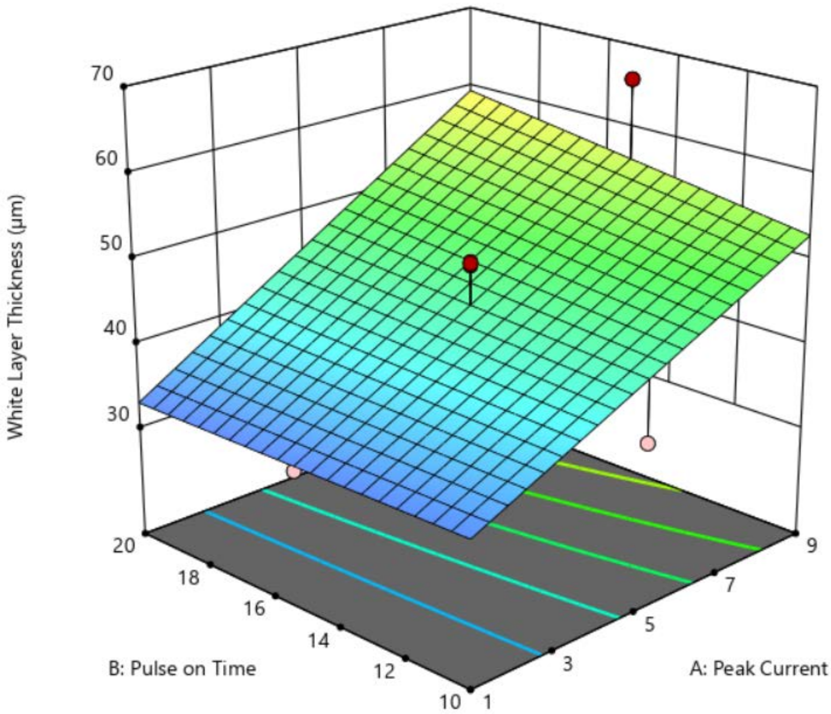

Figure 3. Surface Plot for RL with Peak Current and Pulse on Time.

Table 6. Analysis of Variance for Recast Layer Thickness.

Source	Sum of Square	DOF	Mean Square	F Value	P value	
Model	2033.02	6	338.8367	8.36	0.0007	Significant
A-Peak Current	1322.5	1	1322.5000	32.64	<0.0001	
B-Pulse on Time	22.5	1	22.5000	0.5553	0.4694	
C-Voltage	233.29	1	233.2900	5.76	0.0321	
AB	25.21	1	25.2100	0.622	0.4444	
AC	423.4	1	423.4000	10.45	0.0065	
BC	6.13	1	6.1300	0.1512	0.7037	
Residual	526.77	13	40.5208			
Lack of fit	526.62	8	65.8275	2218.89	<0.0001	Significant
Pure Error	0.1483	5	0.0297			
Cor Total	2559.79	19				

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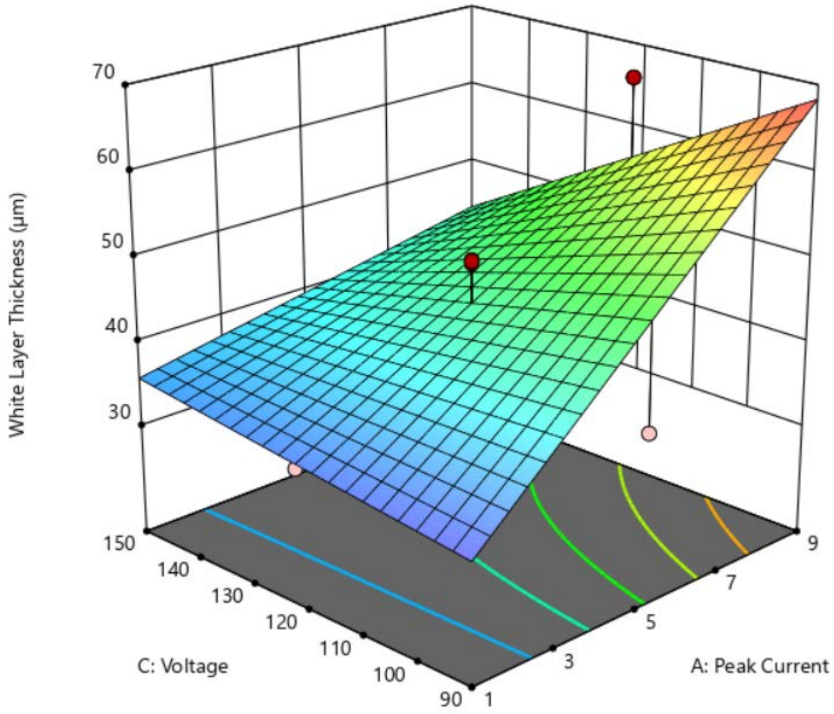

Figure 4. Surface Plot for RL with Peak Current and Voltage.

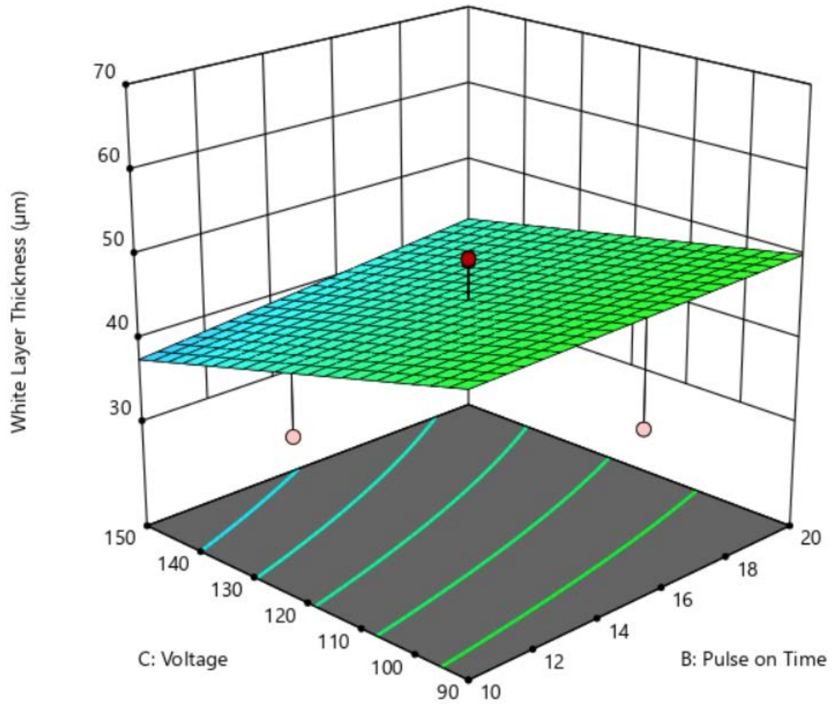

Figure 5. Surface Plot for RL with Pulse on Time and Voltage.

Model Validation

Model was validated for assessing that the evolved response surface model can forecast recast layer thickness behavior successfully or not. This is done through point prediction ability of Design Expert and the variables were selected for validating the model. Figure 6 depicts the SEM micrograph for validating the data. Table 7 represents the result of validation with the set of EDM variables. The table shows that the residual error is below 3.13%, which specifies the adequacy of the model.

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Table 7. Model Validation of Recast Layer Thickness.

Sl. No.	Input Parameters	Predicted RLT (µm)	Validated RLT (µm)	% Residual Error
1	Peak Current = 5A; Pulse on Time = 15µsec; Voltage = 120V	44.75	46.2	3.13%

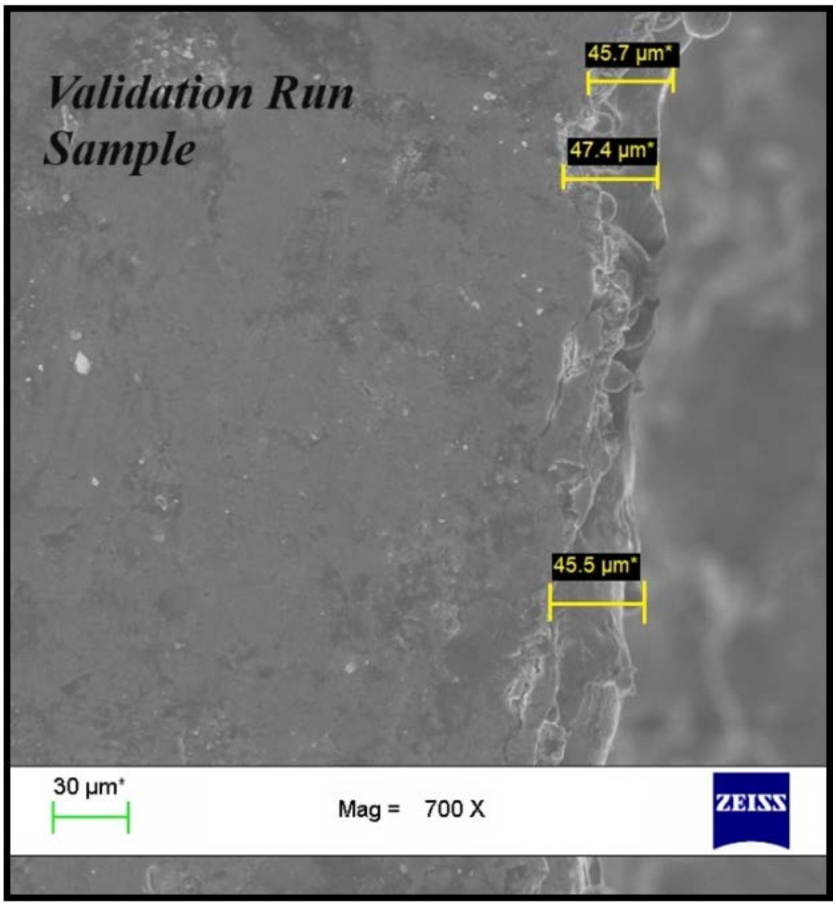

Figure 6. **Image for RLT Sample of Validation Run.**

Conclusion

The assessment conducted to optimize the deposition of the recast layer over the machined surface of Die Steel D3 post-EDM using copper electrodes yielded the following inferences:

The extent of recast deposition was estimated using Carl Zeiss Evo 50 SEM machine. The average of the recast layer thickness was considered to analyze the influence of EDM variables. SMSS and lack of fit tests were performed to find the model type for the recast layer trend, and both tests suggested a Two Function Interaction model.

Analysis of Variance for 2FI model was conducted for recast layer thickness and the F-value = 8.36 outlays the significance of the model. For this model, current (A), voltage (C) and peak current-voltage (AC) are significant model terms.

It was found that duration (p-value = 0.4694) was the minimal affecting factor amid selected variables for recast layer thickness, which aligns with the previous literature. Peak current is the major dominating variable (p-value < 0.0001) for the present model, substantiating the previous research on RLT.

#The impact of current and on duration is almost linear towards RLT and higher deposits of recast layer are observed at elevated levels of these parameters. Lower RL can only be attained by setting a lower current and duration. The influence of lower voltage is not much on recast layer thickness at a lower level of current. However, at a higher peak current level, the RL formation decreases with an increase in voltage.

Minimum variation in the deposition of recast is observed while considering voltage and duration. A lower voltage and duration are suggested to minimize the

deposition of the recast layer during EDM of die steel D3.

The developed recast layer is the solidified debris removed during the process of machining. This layer will hinder the further machining process to a certain extent, which may influence its effectiveness. Thus, minimum values for the chosen variables must be set to minimize the deposition of recast.

The validation of the model shows that the residual error is below 3.13%, which specifies the model's adequacy.

Conflict of Interest

The authors declare no conflict of interest.

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