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Influence of Process Parameters on the Microstructural Characteristics and Mechanical Properties of Recast Layer Thickness Coating on Die Steel Machined Surface after Electrical Discharge Machining

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ABSTRACT

The surface layer machined after electrical discharge machining (EDM) is different from it after traditional methods, and studying the surface layer structure machined by this method will contribute significantly to the selection of finishing methods. In this study, the surface layer of SKD61 steel after EDM using copper (Cu) electrode was analyzed. Technological parameters, including discharge current (Ie), pulse on time (Ton), pulse off time (Tof), and voltage (Ue) were used in the study. The minimum recast layer thickness (RLT) was determined using the Taguchi method. The results showed that Ie, Ton, and Tof were significant influences on RLT, and Ue was insignificant. Minimum value of RLT = 3.72 µm at process parameters Ie = 1 A, Ton = 50 µs, Tof = 12 µs, and Ue = 30 V. The machined surface layer after EDM is inconsistent with the workability of the product, and it should be removed from the machined surface.

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1. INTRODUCTION

Electrical discharge machining (EDM) is widely used to shape the surface of moulds and tools. In this method, the material of the workpiece with any mechanical properties can be processed by the electrode with much lower mechanical properties [1]. This will facilitate overcoming difficulties with the mechanical requirements of tools in traditional machining. However, the EDM machining principle is practiced by the high thermal energy of the sparks to cause the melting and evaporation of the surface material layer of the workpiece and electrode. Therefore, the quality of the machined surface in EDM is also different from it in traditional machining. The white layer on the machined surface should be removed by grinding or polishing [2]. Therefore, the research results to clarify the quality of the surface layer after EDM, and it will make an important contribution to reduce the cost of machining of the surfaces and helping to lower the manufacturing costs of the product.

Surface quality after EDM affects the durability of the mould surface. The mechanical and chemical properties of the white layer on the EDM surface not only affect the surface strength of the product, but it also directly affect the machining productivity and electrode wear in EDM [3]. White layer that form continuously on the workpiece surface during machining tend to lead to increased machining productivity and reduced electrode wear. The type of workpiece material and the different machining methods in EDM (Die sinking EDM or Wire EDM) have little effect on recast layer thickness (RLT) (or white layer thickness) [4]. The energy of the spark is a strong influence on the RLT. Also, besides the energy level of the spark and the type of work (finished or roughed) will strongly influence the hardness of the white layer. The increased spark energy leads to increased hardness of the RLT, and the hardness of the machined surface after

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roughing is higher than that in finishing. The residual stress that appears in the white layer is the residual tensile stress, and this will adversely affect the workability of the product surface. The white layer of AISI 316SS surface after EDM is the material layer with many phases, of which austenite is the most common, and the residual tensile stress in RLT is quite large [5]. Although the hardness of the surface layer is higher than that of the substrate, its wear resistance is very low. The workpiece surface layer affected by the heat energy of the spark after the EDM consists of 3 layers of RLT, heat affected zone (HAZ), and tempered layer [6]. RLT increased with discharge energy (Ee) increase. The organization of the main phase on the white layer includes martensite and austenite [7]. HAZ is a material layer formed by the phase transition from the substrate, the phase transition temperature is the temperature of the electric spark that has been reduced by transmission through the white layer. The exact size of the RLT and HAZ depends mainly on the technical parameters, and the larger the pulse energy, the larger the size of these layers. Increased spark energy (Ee) will result in an increased RLT, and this effect on the RLT is quite apparent [8]. HAZ is significantly affected by the pulse time (Ton). Increased discharge current (Ie) will cause Ee to be increased, and the phenomena of short circuit and arc discharge are responsible for the increase of surface roughness (SR) and the uniformity of the white layer on the machining surface is reduced [9]. An increase in Ee led to an increase in the size and number of adhesion particles, microscopic cracks, micro-voids, and porosity of the machined surface layer. Micro-cell cracking caused by residual thermal stress, and its size and quantity depend on the machining condition [10-12]. The influence of Ton and Ie on the surface layer of the workpiece and electrode is quite strong [13]. The increase in Ton resulted in a significant increase in the RLT of both the workpiece and the electrode surface. However, the increase in Ie caused a negligible change in their RLT. The radius of the plasma channel will increase with the increase of the discharge time, however, the pulsed thermal energy is impacted on the workpiece surface and the discharge density on the machining surface is reduced [14]. The influence of Ton, Ie on RLT and HAZ of the machining surface after EDM was shown by numerical simulation method combined with research experiment [15]. Results showed that the increase of Ton = 8-25 µs resulted in a large increase in RLT, and Ie = 8- 24 A resulted in a slight decrease in RLT. This is because the change of Ton and Ie leds to the change of the spark energy and the plasma flushing efficiency. The increase in the spark energy leads to the size of the globule and the radius of the craters on the machining surface is larger, and the porosity of the white layer is greater than [16]. The RLT in EDM for Ti-6Al-4V was accurately determined using the RSM method [17]. The Ie, Ton, and Tof all strongly influence the value of RLT. The best technological parameter set for RLT and HAZ is the smallest as determined by the Taguchi method [18]. Taguchi combined with ANFIS was also able to accurately determine the dimensions of the RLT [19]. The results showed that Ie, Ton and Tof strongly influenced RLT and that RLT was smallest at Ie and Ton at the lowest, and Tof was at the highest. The white layer on the machined surface after EDM was precisely determined by modeling by the FEA method [20]. The results showed that the random distribution of the sparks that led to the solid structure of the RLT and HAZ is uneven. Using the same algorithm, FEA showed that layers of materials with different organizations were formed on the workpiece surface by the influence of sparks [21]. This has led to the physical and chemical properties of the RLT layer being different from that of the substrate. Many methods combining simulation with experiment have been introduced to determine the most suitable value of RLT including RSM, Taguchi, ANN, etc [22-24]. However, due to the complexity of the machining mechanism and the level of the technological parameters that vary over a wide range, the results are often influenced by large noise. Therefore, the Taguchi method is still the most commonly used today.

The survey results have shown that the influence of technical parameters on the white surface layer in EDM machining types is different. The value of the RLT of each surveyed case is different, so it is essential to accurately determine the change of RLT and its exact value. In this study, the effects of Ie, Ton, Tof, and Ue on the RLT of the machined surface layer after EDM with Cu electrode were studied. The workpiece is used with SKD61 die steel. Minimum RLT is determined with the respective technology parameter set, and the surface quality has been analyzed and evaluated.

2. THEORY OF THE TEMPERATURE EFFECTS OF DISCHARGES

To this day, precise control of spark formation and maintenance in EDM is not possible. The reason is that the values of these technological parameters are constantly changed during the machining process (see Figure 1) [8]. In practice, determining the exact values of t_d and t_e is impossible because it depends on many factors including surface roughness of the electrode and workpiece, physical and chemical properties of the material, and type of dielectric fluid, conditions in the gap between the electrode and workpiece, etc. In the present calculation, the value of Ton will be chosen to approximate to t_e. This causes the EDM machining mechanism to be unclear, and it also causes difficulty in controlling productivity, machining quality, and machining accuracy in EDM.

The RLT of the surface layer in the EDM depends on the energy of the sparks and the propagation of the thermal energy of the sparks into the machining surface layer. The thermal energy of discharge sparks depends on technological parameters including Ue, Ie, Ton, and Tof [9]. Ue, Ie, and Ton are the parameters that strongly affect the energy of the discharge sparks [19]. The energy of the discharge sparks is determined by Equation (1).

$$E_e = \int_0^{te} u_e(t).i_e(t).dt \approx u_e.i_e.t_{on} \quad (1)$$

The thermal energy of each spark (qe) is determined by Equation (2) [8].

$$E_e = \int_0^{te} u_e(t).i_e(t).dt \approx u_e.i_e.t_{on} \quad (2)$$

where, r_e is the radius of the spark.

The amount of heat transferred to the surface layer of the workpiece is assessed by the coefficient of heat distribution to the surface of the workpiece ωq= qw/qe, Figure 2a. Where qw is the amount of heat transferred to the surface of the workpiece and it is shown in Figure 2b.

Heat propagation into the machining surface layer in EDM is influenced by the thermal and physical properties of the electrode material, the dielectric fluid, and the workpiece material. The greater the thermal conductivity of the electrode and the solvent, the lower the thermal energy in the machining area, and this leads to a decrease in heat transfer to the workpiece surface. Conversely, a good workpiece thermal conductivity will lead to an increase in the heat-affected workpiece surface layer thickness. This has resulted in the machined surface layer after EDM shown in Figure 3 [20]. This change will directly affect the melted and evaporated workpiece quantity, the change of the mechanical and physical characteristics and the surface material layer structure, the topography formation of the machined surface, and machining accuracy. The RLT formed by the electrode material and melted and evaporated workpiece was not pushed out by the dielectric solution to initiate the discharge gap. They combine with the compound of the dielectric solution separated by the spark to form another compound, and they adhere firmly to the machining surface. AHZ layer appears on the surface by the impact of the heat of sparks that leads to phase change of the substrate layer. The RLT after EDM is low, and it must be removed from the surface of the product. The WLT modification study, therefore, contributes to the exact determination of the layer to be removed and reduces the time and cost of the next finishing work.

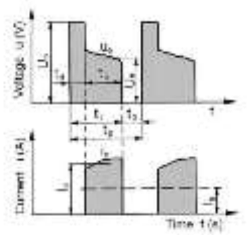
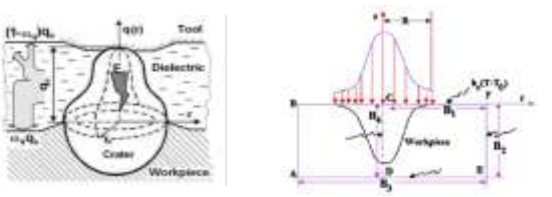


Figure 1. The variation of U and I in EDM. U_o - Open gap voltage, Ue - Discharge voltage, t_d - Ignition delay time, t_e - Discharge duration, t_i (Ton) - Pulse on time, t_o (Tof) - Pulse off time, t_p - pulse cycle time, Ie - Discharge current, I_a - Average current



(a) Thermal model in EDM (b) Thermal model imparts to workpiece in EDM

Figure 2. Thermal in EDM

3. EXPERIMENTAL DESIGN

Experimental studies are performed on the CHEMER - EDM machine (CM323C- Taiwan). SKD61 die steel is used as a workpiece and its dimensions are 15 x 15 x 10 mm, and the electrode material is copper (Cu) and its diameter is Ø10 mm. The levels of the technical parameters are selected in EDM finishing, and they are shown in Table 1. The Taguchi method was used to design the matrix of the experiment (L25). The surface layer of the workpiece after EDM was investigated and analyzed for the surface layer structure. Research studies published by Habib et al. [5] have shown that the AHZ is the layer formed has significantly improved the working ability of the templates, and RLT is the layer at the top of the machined surface but it negatively affects the workability of the product (see Figure 4). Therefore, this study to accurately determine the value of RLT, because this will significantly contribute to reducing the cost of material consumption. and finish machining next.

The surface roughness (SR) was measured using a contact probe (SJ-210) type profilometer (MITUTOYO, JAPAN) with an evaluation length of 5 mm. Two measurements were acquired for each test sample and the average value of each measurement was considered. The

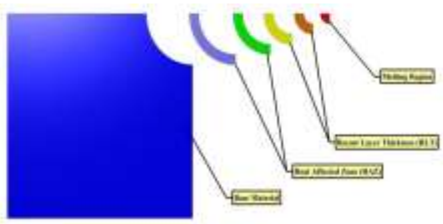


Figure 3. Layers of the machined material on the machined surface after EDM [20]

TABLE 1. Experimental results for the conducted machining trials.

Trial	Ie	Ue	Ton	Tof	RLT(μm)
1	1	30	18	9	4.023
2	1	40	25	12	3.629
3	1	50	37	18	3.277
4	1	60	50	25	4.284
5	1	70	75	37	6.755
6	2	30	25	18	6.199
7	2	40	37	25	6.805
8	2	50	50	37	6.856
9	2	60	75	9	6.552
10	2	70	18	12	5.799
11	3	30	37	37	7.965
12	3	40	50	9	5.243
13	3	50	75	12	4.933
14	3	60	18	18	7.911
15	3	70	25	25	7.430
16	4	30	50	12	4.738

Figure 4. Layer formation on the machined specimen

surface morphology was acquired using a scanning electron microscope (Jeol-6490 JED-2300, JEOL JAPAN) and optical microscope(OPM).

4. RESULT AND DISCUSSION

4. 1. Effect of Process Parameters on WLT Coating

Analysis of variance (ANOVA) of RLT is shown the influence of parameters on RLT (see Tables 2 and 3). Based on the value of the coefficient Fisher (F) showed that process parameters including Ie (F = 13.83), Ton (F = 8.08), and Tof (F = 7.52) are a significant influence on RLT, and Ue (F = 2.44) is insignificant influence on RLT. Where Ie is the most significant influence, Tof is the 2nd most significant influence, and the smallest influence is Ue.

The change of the technological parameters has led to the RLT being altered (see Figures 5-8). The increase in current (Ie) leads to the increase in the energy of the sparks (Ee), and this causes the increase of the RLT, Figure 5. e = 1-3 A, it resulted in the RLT being slightly changed, the cause was that the spark energy was not significantly affected. Therefore, the thermal energy of the sparks causes the amount of electrode material and the workpiece to be melted and evaporated with a small change. RLT has been drastically changed with I = 4-5 A. Compared with the RLT at I = 1A, the RLT at I = 5 A was increased by 179.2%. Ue increase is shown in Figure 6. Ue = 30 - 50 V led to RLT being increased, but when U> 50 V led to a decrease in RLT. The reason this happens is that a change of U leads to altered machining productivity, and this will affect the amount of electrode material and workpiece adhering to the machining surface. RLT is maximum at U = 50 V and it is minimum at U = 30 V. Figures 7 and 8 show the effects of Ton and Tof on RLT, and the influence of these process parameters is contradictory. In theory, an increase in Ton and a decrease in Tof will lead to increase machining productivity, and this leads to an increase in RLT. This could be due to the change of Ton and Tof leading to the increase in the plasma flushing efficiency, and this has

TABLE 2. Analysis of variance for RLT

Factor	DF	SS	V	F	P	Ranking
Ie	4	213.11	53.276	**13.83**	0.001	1
Ue	4	37.53	9.382	2.44	0.132	4
Ton	4	115.79	28.948	**7.52**	0.008	3
Tof	4	124.50	31.126	**8.08**	0.007	2
Error	8	30.81	3.851	-	-	-
Total	24	521.74	-	-	-	-

TABLE 3. ANOVA for S/N ratio of RLT

Factor	DF	SS	V	F	P
Ie	4	215.31	53.827	28.64	0.000
Ue	4	16.40	4.099	2.18	0.162
Ton	4	63.23	15.809	8.41	0.006
Tof	4	104.14	26.036	13.85	0.001
Error	8	15.04	1.879	-	-
Total	24	414.12	-	-	-

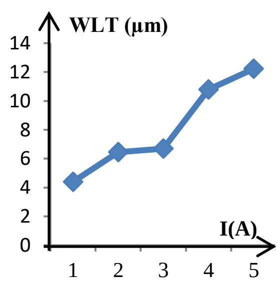


Figure 5. Effect of Ie on RLT

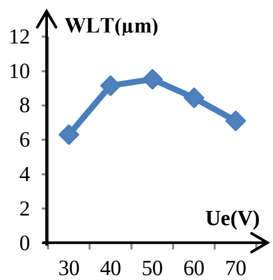


Figure 6. Effect of Ue on RLT

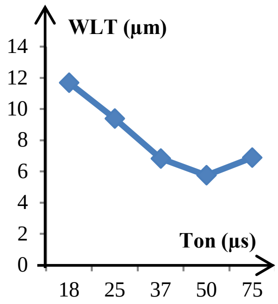


Figure 7. Effect of Ton on RLT

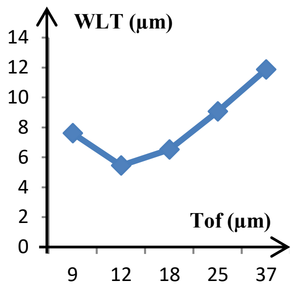


Figure 8. Effect of Tof on RLT

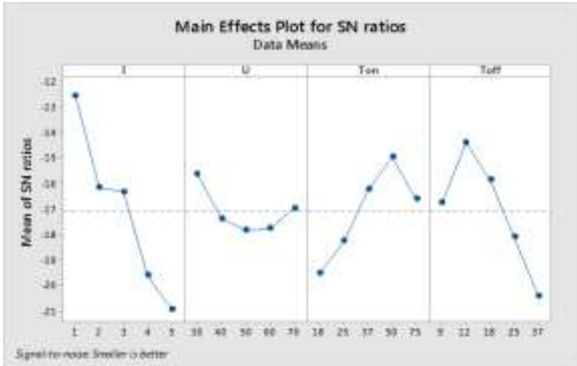


Figure 10. Effect of process parameters on S/N ratio of RLT

resulted in the molten and evaporated mass of the workpiece and the electrode being ejected from the crater easier [15]. Hence the amount of material deposited on the machining surface is reduced, and it leads to a decrease in RLT. The Ton that is too large will lead to the predominant time to pulse during machining, thus the time to eject the dielectric fluid and chip from the discharge gap is also reduced, and the time for the dielectric fluid to recover is very short. This will lead to an unstable machining process and multiple short-circuit pulses, and local arcing so the RLT is small. Hence, the RLT is unevenly distributed on the machining surface, Figure 9. Increased Tof can lead to increased machining productivity, and RLT increased accordingly. RLT is minimum at Ton = 50 µs and at Tof = 12 µs.

4. 2. Determine the Optimal Value of RLT The RLT is formed on the machined surface layer after EDM, which needs to be removed by the next finishing method. Therefore, the S / N coefficient of RLT is "*The lower is better*". The ANOVA result of S / N of the RLT is shown in Table 4, and the confidence interval of the ANOVA result of the S / N is 95%. The results showed that Ie (F = 28.64), Tof (F = 13.85), and Ton (F = 8.41) are parameters that significantly affect the S / N ratio of RLT. It is the basis to build the formula to determine the optimal value of RLT (RLTopt), and significant parameters including Ie, Ton, and Tof were used to determine RLTopt. Figure 10 shows the optimal technology parameters including Ie = 1A; Ton = 50µs, Tof = 12µs; Ue = 30 V. The optimal value of RLT is determined by formula (3), the calculation results of RLToptcal = 3.50 µm. Verifying the experiment with the

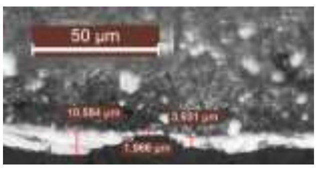


Figure 9. RLT of a machined surface at Ton = 50 µs

optimal parameters has identified RLTopt = 3.72 µm, and the difference between calculation results and experimental results is only 6.21%. This proves that the computational model can accurately predict RLT.

$$RLTopt = I1 + Ton4 + Tof2 - 2.T \quad (3)$$

4. 3. Surface Topography Analysis of Machined Surface The machined surface is composed of many craters and micro-voids, and they are arbitrarily distributed, Figure 11. This is because the energies of the sparks are randomly generated and arbitrarily distributed in the machining area. The material layer of the workpiece surface and electrode is caused by the enormous thermal energy of the electric sparks (8000-12000 ^{0}C) to melt and evaporate, and it is immediately cooled by a dielectric fluid [3]. Consequently, many of the globules and debris are adhered to the machining surface, Figure 12. The external surface tension of the dielectric solution causes the geometry of craters and particles to adhere to the radius of curvature or spherical. Adhesion particles are formed when the material is melted and evaporated. Therefore, he adhesion strength of the particles to the machining surface can be in the form as shown in Figure 13. The machining characteristics of EDM differ from that of traditional machining, and it has resulted in the profile of the machined surface layer after EDM being very complex, Figure 14. This is directly related to the method used and the finishing cost. A lot of microscopic cracks appeared on the workpiece surface after EDM, Figure 15. This is because the electrode and workpiece material on the workpiece surface at very high temperatures cools very quickly, and residual thermal stress occurs at the surface layer appears [3]. Any cracks distributed on the machined surface and depth developed in a direction perpendicular to the machined surface, Figure 16. The depth of microscopic cracking is approximately equal to that of RLT, and micro-voids also exist in RLT. EDS of the post-EDM surface layer showed that % C was greatly increased (≈ 8.84%) and a sizable amount of % Cu appeared on the surface layer, Figure 17. The increase in % C is because the oil dielectric solution is cracking by the thermal energy of the sparks, and the increase of % Cu is due to molten and evaporation of the material on the electrode surface having penetrated the machined surface. The appearance of these elements under high - temperature conditions has led to a change in the composition of the element compounds and phases at the machined surface layer, Figure 18. Since a sizeable amount of element C is diffused into the machining surface layer, it combines with element Fe and some alloying elements in steel SKD61 to form the carbides including Fe2C, Fe3C, Fe7C3, V8C7, and Mo3C7. This led to a change in the physical and chemical properties of the surface layer, and the hardness of RLT was smaller than that of HAZ and base metal, Figure 19. The reason may be that the majority of the white layer formed phases are austenites [15]. This will affect the product's ability to work. The thickness of RLT at the optimum condition is shown in Figure 20. Although the distribution has been significantly improved, the uniformity of this layer on the machined surface is still very low. This makes it more difficult to choose the correct removal thickness for the next finishing.

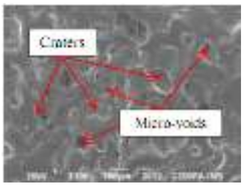


Figure 11. EDM surface morphology

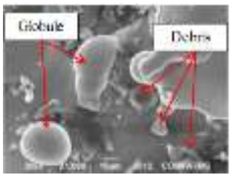


Figure 12. Surface texture after EDM

Figure 13. Globule formation and residue of melted material in recast layer

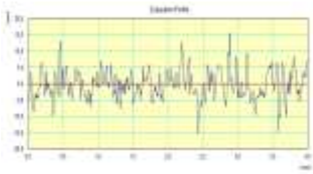


Figure 14. Profile of the machined surface

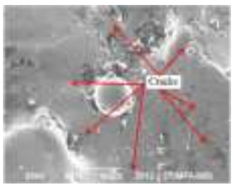


Figure 15. Cracks distribution

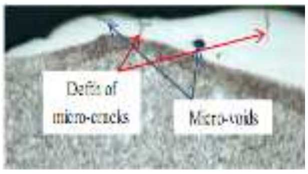


Figure 16. Recast layer and heat-affected zone induced by EDM

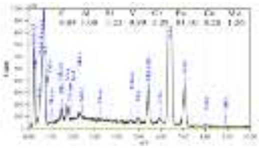


Figure 17. EDS elemental analysis of surface after EDM

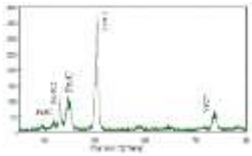


Figure 18. XRD pattern of a machined surface

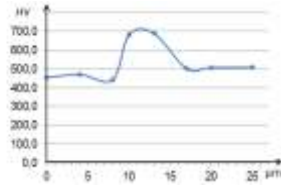


Figure 19. Profile of micro-hardness on the EDMed surface

Figure 20. Recast layer thickness on a machined surface

4. CONCLUSION

In the present study, the surface layer of the SKD61 die steel in EDM using Cu electrode on machining SKD61 was analyzed and evaluated. From the experimental investigation, the following conclusions were made.

- Peak Current (Ie) is the most significant influence and Ue is the insignificant influence on surface morphology.
- The minimum RLT was found at Ie = 1 A, Ton = 50 µs, Tof = 12 µs and Ue = 30 V with the unevenly distributed thickness of the white layer on the machining surface.
- The removed layer thickness of the machining surface in EDM is to be approximately 2-3 times greater than that of the RLTopt.
- The main research directions include integrating vibration into the EDM process can lead to the smallest RLT and the size of the RLT to be more uniform.
- The utilization of suitable powder mixed in the dielectric fluid in EDM can reduce the size of the RLT considerably.

5. ACKNOWLEDGMENT

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Persian Abstract

چکیده

لایه سطحی ماشین کاری شده پس از ماشینکاری تخلیه الکتریکی (EDM) عد از روش های سنتی با آن متفاوت است و مطالعه ساختار لایه سطحی ماشین کاری شده با این روش به طور قابل توجهی در انتخاب روش های اتمام کمک می کند. در این مطالعه ، لایه سطحی فولاد SKD61 پس از EDM با استفاده از الکترود مس (Cu) مورد تجزیه و تحلیل قرار گرفت. پارامترهای فن آوری ، از جمله جریان تخلیه (IE)، پالس در زمان (تن) ، زمان پالس (Tof)، و ولتاژ (Ue) در مطالعه استفاده شد. حداقل ضخامت لایه بازسازی ((RLT) با استفاده از روش تاگوچی تعیین شد. نتایج نشان داد که Ie، Ton و Tof تأثیر قابل توجهی بر RLT دارند و Ue ناچیز است. حداقل مقدار RLT = 3.72 میکرومتر در پارامترهای فرآیند Ie = 1 A، Ton = 50 میکرو ثانیه ، Tof = 12 میکرو ثانیه و Ue = 30 ولت از سطح ماشینکاری شده برداشته شود.