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Investigation and Optimization of the Recast Layer Thickness of 9XC Steel Generated by the Tungsten Compound Powder Mixed-EDM Process

Dao Cong Thang[1*], Le Van Tao[2], Do Manh Tung[1], Huu Vinh Ta[2]
[1]Mechanical Engineering Department, Le Quy Don Technical University, Ha Noi, Viet Nam
[2]Advanced Technology Centre, Le Quy Don Technical University, Ha Noi, Viet Nam
[*]Corresponding author: thangdao1109@gmail.com

Abstract— *In this paper, the recast layer thickness (RLT) of 9CrSi alloy tool steel machined by the EDM process with tungsten compound powder was explored. The influence of key process variables, including peak current (I_p), pulse on time (T_{on}) and powder concentration (C_p) on RLT was shown through the implementation 15 experiments followed the Box - Behnken design in Response Surface Methodology (RSM), set up a full mathematical model for RLT using Design Expert software version 12, then applied analysis of variance (ANOVA) with 95% confidence and a significance level of 5% to evaluate the accuracy of the RLT development model. The accuracy of the developed model has been verified by the values of the coefficients being R^2=0.9948; Adjusted R^2=0.9853; Predicted R^2=0.9398. Finally, the Desirability Approach (DA) method was used to optimize the process variables for reaching RLT_{min}. The results show that the minimal RLT is 18.514 µm at I_p=4 A, T_{on}=50 µs and C_p=10 g/l.*

Keywords— *EDM, PMEDM, tungsten compound powder, RLT, DA.*

I. INTRODUCTION

Tool steel is commonly used in the manufacturing industry to create tools and components for machining and shaping various materials such as metals, plastic, wood… which require high performance, strength and precision in demanding applications [1,2]. 9CrSi tool steel is an alloy steel whose main components include Chromium (Cr) and Silicon (Si), which helps increase hardness, wear resistance and cutting strength. This steel has good hardenability and performace, retains high sharpness after heat treatment. Due to such characteristics, they are popular choice for cutting tools and cold forging dies. Although widely used in various industries, machining of 9CrSi alloy tool steel is still a major concern for researchers worldwide because of its high hardness and brittleness, and poor machinability. Therefore, electro-discharge machining (EDM) is used for machining 9CrSi tool steel because of its contactless machining procedure. EDM is a material erosion process that mainly uses electrical energy and converts it into thermal energy through a non-continuous discharge cycle occurring between the tool and the workpiece in a dielectric environment. In addition to its many benefits, the EDM process has many drawbacks, including high tool wear rate, low material removal rate, and poor surface quality [3,4]. By incorporating conductive particles into the insulating dielectric fluid, a technique known as powdermixed electro-discharge machining (PMEDM), the aforementioned EDM process limitations have been addressed. Because the dielectric fluid's insulating capacity has decreased, the machining performance has increased. When conductive powder is added to the dielectric fluid during the spark discharge process, the electrode gap and spark intensity simultaneously rise. Together with increased machining performance, the sample's surface quality including microhardness, surface roughness, and surface morphology also shows positive trends as a result of the spark discharge process being more stable [5–7].

The first investigation into how adding powders of Al, Fe, and C to the dielectric fluid affected the surface quality and machinability of samples in the PMEDM process was published in 1980 [8]. Numerous follow-up research on various kinds of electrode materials and powders have now been released. Chen and Lin investigated the use of TC powder and an ultrasonic tool in the EDM method for processing Al-Zn-Mg material [9]. The findings showed improvement in roughness, microhardness, material removal rate (MRR), and tool wear rate (TWR) in contrast to traditional EDM procedures. In their study [10], S. Tripathy and D. Tripathy demonstrated that the addition of Cr powder to the EDM process enhanced the microhardness, microcracks, and surface morphology of H-11 steel. According to Van Tao Le's research [11], when tungsten compound powder is used in conjunction with appropriate technological parameters, the sample's surface roughness is decreased by 57.984%, its surface morphology is enhanced (smooth surface, few microcracks), and its microhardness of the surface layer increases by up to 129.167% when compared to the traditional EDM process for SKD61 steel. Meanwhile, the author of the later paper [12] employed tungsten compound powder, which was added to the EDM process, to machine AISI H13 steel. As a result, machining performance (including MRR and TWR) and recast layer properties are greatly influenced by peak current (I_p), pulse on time (T_{on}), and powder concentration (C_p). Specifically, MRR and TWR tend to increase as I_p, T_{on}, and C_p increase, while recast layer thickness (RLT) formed by PMEDM decreases by 48.982% when compared to EDM. The research of Schubert [13] indicated utilizing tungsten powder mostly focused on the hardness investigation. The hardness of different die steel materials has been enhanced from (465-652) HV to (1072-1410) HV, respectively when adding 15 g/l W powder into the dielectric fluid [14]. The addition of 8 g/l W powder concentration into the hydrocarbon-based dielectric fluid in PMEDM resulted in an increase of aluminium surface hardness from 106.67 HV to 218.33 HV [15].

There have been several researchs with different powders in the EDM process to achieve certain effects aimed at increasing machining productivity. However, studies on the recast layer thickness (RLT) when adding tungsten compound powder into the dielectric fluid for 9CrSi alloy steel processed by the PMEDM are still limited. Hence, this research aims to investigate the influence of the pulse on time (T_{on}), the peak current (I_p) and the powder concentration (C_p) on RLT of 9CrSi tool steel during the EDM process with the addition of tungsten compound powder. This study focus on establishing predictive model of the RLT by utilizing RSM for the processing of 9CrSi tool steel. From the prediction model, the effect of process parameters on machining performance can be analyzed and evaluated. In addition, to improve machining accuracy, in this study, the optimal domain of process variables to achieve RLT_{min} was found.

II. Materials And Methods

This experiment uses 9CrSi tool steel imported from China. Its chemical composition contains 0.85%C-1.4%Si-1.2%Cr-0.2%Cu-0.03%P-0.15%Mo-0.35%Ni-0.03%S-0.4%Mn-0.1%W-0.13%V-0.03%Ti-balanced Fe (% weight). Tungsten compound powder (WC-727-6) with less than 31µm of particle diameter has a chemical composition including 5.56%C-11.9%Co-0.02%Fe-82.5%W-0.02% other components supplied by manufacturer Praxair Surface Technologies. Copper was used as electrode material and the dielectric fluid was EDM 2 oil provided by the manufacturer Shell which was used in this experiment.

Samples were machined using an electrical discharge machine (model: CNC - 460 EDM from the Aristech Company as shown in Fig. 1e). The sizes of specimens before and after machining was in Table 1. Before processing using the PMEDM method, the samples were ground with extreme accuracy, taking into account both geometric errors (0.02 mm) and geometric sizes (0.01 mm). They are then securely and carefully attached to the CNC-460 EDM machine. The dimensions of the tank are D × W × H = 420 × 320 × 320 mm, holding a maximum of 43 liters of dielectric fluid. Then, tungsten compound powder is added to the dielectric fluid in the tank. As shown in Table 1, the powder was added to the dielectric fluid at various concentration levels.

The following criteria were used to choose the process parameters: the electrical parameters were chosen based on the summary of studies and the controller configuration established in the electrical discharge machine (model: CNC-460 EDM). Additionally, the goal of this study is to examine how electric parameters affect the recast layer thickness. In addition, the influence of peak current and pulse on time on machining performance and recast layer properties of 9XC steel had the strong impact [12,16,17] so they were selected. Beside, powder concentration levels of tungsten compound powder was selected combine the electrical parameters selected above to investigate the tests because of understanding the electrical and thermal properties of it [18,19]. As shown in Table 1, other electric parameters such as discharge voltage, electrode polarization, and pulse off time remain constant throughout the experiment. The concentration selection of powder is based on the combination of the trials and the therm and electric properties of the powder.

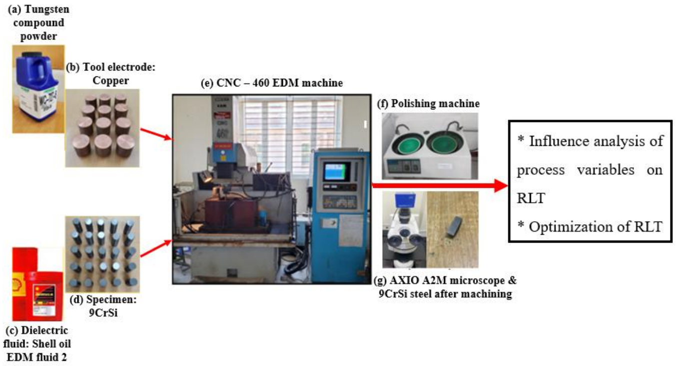

Fig. 1. Experimental diagram.

TABLE 1. Conditions in experimental investigation.

Deposition Condition	Detail
The peak current (I_p-A)	4A; 6A; 8A
The pulse on time (T_{on}-µs)	50 µs; 100 µs; 150 µs
The pulse off time (T_{off}-µs)	50µs
The dielectric fluid	Shell EDM Fluid 2
The polarity of electrode	Negative (-)
The material of the tool electrode	Cu (99%)
The current voltage (V)	120V
The powder concentration (C_p-g/l)	0 g/l; 10 g/l; 20 g/l
Dimension of the sample	Diameter x Length = 20 x 50 mm
Dimension after machining of the sample	Diameter x Length = 20 x 49.5 mm

- *The determined method of recast layer thickness (RLT)*: The specimens' surface is cut in cross-section to reveal the recast layer. They were then polished using fine armor paper with a grain size of 2000. Then, as seen in Fig. 1g, they were felt-polished by polishing machine. The samples were then etched with a solution named Nital containing 5% HNO_3 and 95% alcohol for 3-4 seconds. The optical microscope (AXIO-A2M) examined the recast layer of surfaces. Using optical microscopy, the recast layer image of the surfaces in the area has been recorded. Following that, the Axiovision Cam 4.82 program processed this optical microscope micrograph to identify the $S_{\text{recast layer (region i)}}$ and $L_{\text{recast layer (region i)}}$, as shown in Fig. 2. Here, the area and length of the recast layer in the i^{th} region are denoted by the $S_{\text{recast layer (region i)}}$ and $L_{\text{recast layer (region i)}}$. The medium value of the three measuring zones on the cross-section of sample surfaces represented the measurement result of the thickness of the recast layer in each technological mode. Formula (1) is used to determine the medium recast layer thickness value.

$$\text{RLT } (\mu m) = \frac{\frac{S_{RL(regionI)}}{L_{RL(regionI)}} + \frac{S_{RL(regionII)}}{L_{RL(regionII)}} + \frac{S_{RL(regionIII)}}{L_{RL(regionIII)}}}{3} \quad (1)$$

Table 2 describes the experimental matrix with input variable levels and response data, used to establish the regression model for recast layer thickness (RLT). The results obtained are the average values of 3 measurements of RLT of 9CrSi tool steel after machining.

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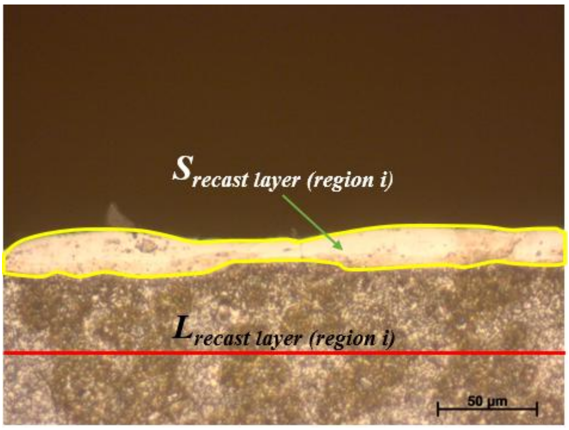

Fig. 2. The method determines $S_{recast\ layer\ (region\ i)}$ and $L_{recast\ layer\ (region\ i)}$ by micrograph of the optical microscope in i[th] region.

TABLE 2. Trial matrix and data of output responses.

Run	Process parameters			Output variable
	I_p (*A*)	T_{on} (*μs*)	C_p (*g/L*)	RLT (μm)
1	8	50	10	22.62
2	6	100	10	20.89
3	6	100	10	20.94
4	6	150	20	23.67
5	4	100	0	22.34
6	8	150	10	23.34
7	6	100	10	20.55
8	8	100	20	22.55
9	4	50	10	18.63
10	6	50	20	18.58
11	8	100	0	25.53
12	4	100	20	20.25
13	4	150	10	21.72
14	6	150	0	23.25
15	6	50	0	23.48

III. RESULT AND DISCUSSION

A. Establishing the prediction model

To establish the mathematical model of output feature – RLT, a regression model of quadratic equation has been offered as follows:

$$y = b_0 + \sum_{i=1}^{n} b_i x_i + \sum_{i=1}^{n} b_{ii} {x_i}^2 + \sum_{i<j} \sum_{j=2}^{n} b_{ij} x_i x_j \qquad (2)$$

Where, b_0, b_i, b_{ii}, and b_{ij} are the coefficients of the regression model; x_i and x_j are process parameters; the variable number is n with $n = 3$; and the output property is y – RLT.

In this study, the coefficients and regression model were calculated and established using Design Expert software version 12. The prediction model for RLT was described as follows:

$$RLT = 21.51875 - 0.4125I_p + 0.016158T_{on} - 0.572792C_p - 0.005925I_pT_{on} - 0.011125I_pC_p + 0.00266T_{on}C_p + 0.150833{I_p}^2 + 0.000072{T_{on}}^2 + 0.012708{C_p}^2 \qquad (3)$$

B. Assessment of the development model

The accuracy of the RLT development model was analyzed by analysis of variance (ANOVA) with a confidence level of 95% and a significance level of 5%, the results are shown in Table 3. If p-values corresponding to the terms of the model are smaller than 0.05, these model elements are meaningful. Therefore, the terms are significant for the RLT forecasting model, including I_p, T_{on}, C_p, $I_p \times T_{on}$, $T_{on} \times C_p$, ${I_p}^2$, ${C_p}^2$. Through the coefficients "R^2", "Adjusted R^2", and "Predicted R^2", the accuracy of the developed model has been verified by the values of these coefficients being 0.9948, 0.9853, and 0.9398 respectively. In this model, the Adeq Precision = 36.4544 is greater than 4, indicating that the proposed RLT model is appropriate.

TABLE 3. ANOVA for predictive model of RLT.

Source	SS	MS	F-value	p-value	Remark
Model	51.80	5.76	105.33	<0.0001	significant
I_p	15.40	15.40	281.88	<0.0001	significant
T_{on}	9.40	9.40	171.97	<0.0001	significant
C_p	11.40	11.40	208.65	<0.0001	significant
$I_p \times T_{on}$	1.40	1.40	25.70	0.0039	significant
$I_p \times C_p$	0.1980	0.1980	3.62	0.1153	not significant
$T_{on} \times C_p$	7.08	7.08	129.50	<0.0001	significant
${I_p}^2$	1.34	1.34	24.60	0.0042	significant
${T_{on}}^2$	0.1207	0.1207	2.21	0.1973	not significant
${C_p}^2$	5.96	5.96	109.14	0.0001	significant
Lack of Fit	0.1831	0.0610	1.36	0.4512	not significant
R^2 = 0.9948; **Adjusted R^2** = 0.9853; **Predicted R^2** = 36.4544					

C. Evaluate the influence of process variables on RLT

Fig. 3 shows the main impact of each process parameter on RLT, it indicated that RLT increases with increasing values of I_p and T_{on} over the entire design space domain. Meanwhile, increasing C_p from 0 to 20 g/l tends to reduce.

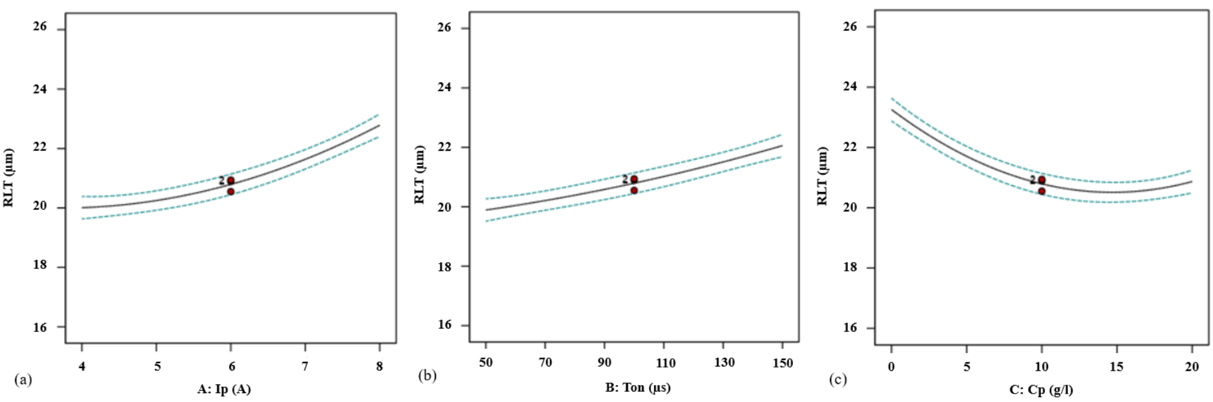

Fig. 3. Main influence of process parameters on RLT.

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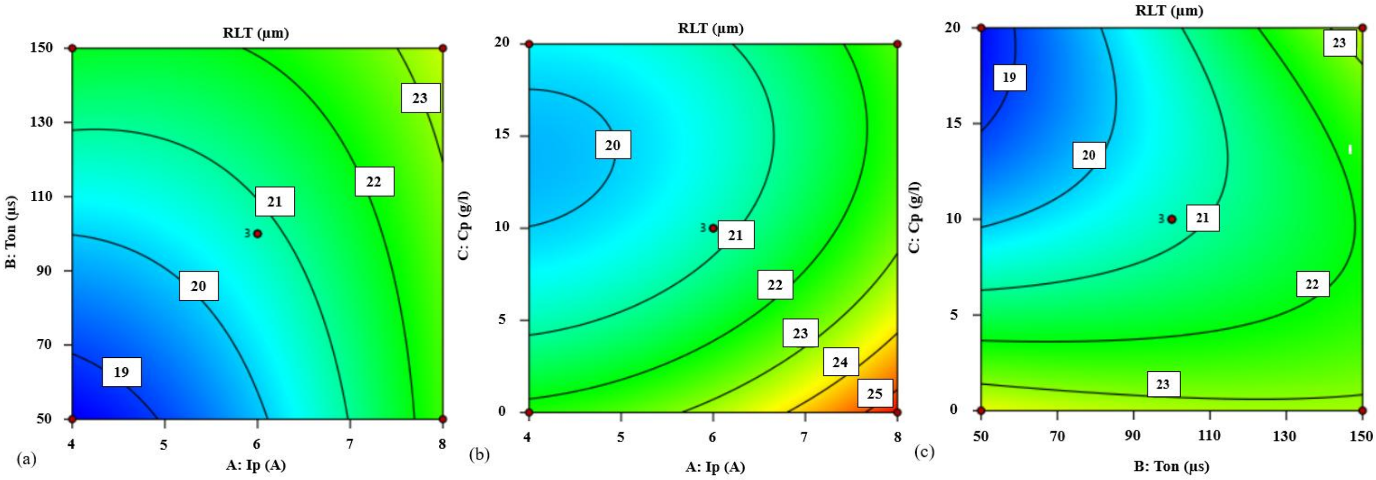

Fig. 4. The incorporated influences of process parameters on RLT: (a) I_p and T_{on}, (b) I_p and C_p and (c) T_{on} and C_p.

The reason is that when I_p and T_{on} increase the energy of the spark increases resulting in the creation of large molten zone, electric spark has longer heat transfer time, so that the RLT increases. Meanwhile, the presence of tungsten compound powder helps to disperse the discharge energy, reducing the temperature concentration on the surface of the workpiece. As a result, the molten zone is smaller, less re-solidified material is produced, leading to a decrease in RLT.

The combined effect of process parameters on RLT is depicted in Fig. 4. It is shown that RLT increases as I_p and T_{on} increase (Fig. 4a), beside RLT tends to decrease with the increase of C_p for all value of I_p and T_{on} (Fig. 4b and 4c). This is explained, higher I_p means greater discharge energy, leading to a larger melted area, longer T_{on} allows more heat transfer**,** increasing the molten depth before solidification resulting in thicker recast layer. Increasing C_p improves dielectric conductivity, disperses energy, and reduces the thermal impact, which prevents excessive material deposition, thereby lowering RLT**.**

D. Optimization of the RLT

Desirability approach (DA) is one of the simplest and widely used methods to optimize process parameters and machining response. Specifically, in this experiment, the input parameters I_p, T_{on}, C_p are optimized to minimize the RLT output value. With this reaching, each output attribute (y_i) is converted into a unique desired function (d_i), $d_i \in [0, 1]$.

If the attribute is expected to minimize, d_i is determined as follows:

$$d_i(y_i) = \begin{cases} 0, y_i < L \\ \left(\dfrac{H - y_i}{H - L}\right)^r, L \le y_i \le H \\ 1, y_i > H \end{cases} \quad (4)$$

where, the upper and lower bound values of y_i are H and L, respectively. r is a parameter named by utilizers ($r > 0$) to depict the shape of d_i. In the end, the desired function D is defined as follows:

$$D = \left(\prod_{i=1}^{n} D_i^{w_i}\right)^{\frac{1}{\sum w_i}} \quad (5)$$

where w_i is the weight, $w_i > 0$ and $\sum_{i=1}^{n} w_i = 1$ with n being the number of attributes/responses.

As a result, the set of optimized values obtained for the parameters using the DA technique through Design Expert 12 software is I_p=4 A, T_{on}=50 µs and C_p=10 g/l. The value of RLT corresponding to the optimal process variables is RLT=18.514 µm.

IV. Conclusion

In this study, the recast layer thickness (RLT) of 9CrSi alloy tool steel machined by the EDM process with tungsten compound powder was investigated. Establishing a prediction model for machining performance, optimizing process parameters, and evaluating the influence of these parameters on RLT were performed. The study also used the Box-Behnken method in RSM to set up the experimental matrix, at the same time set up regression models and used ANOVA analysis of variance with 95% confidence level and 5% significance level to evaluate the accuracy of the RLT development model. The results show that the regression models are highly accurate and can be used to study the influence of process parameters and predict the desired RLT in the entire survey domain. Through the desirability function approach (DA), the optimal response RLT = 18.514 µm corresponds to the process parameters I_p=4 A, T_{on}=50 µs and C_p=10 g/l was found. In future works, other machining performance parameters such as material removal rate (MRR), surface roughness (SR), as well as surface characteristics such as percentage of the surface micro-crack density acreage (PSCDA) and surface morphology of 9CrSi steel before and after heat treatment will be studied for application in the manufacturing industry.

References

[1] Deirmina F, Peghini N, AlMangour B, Grzesiak D, Pellizzari M. Heat treatment and properties of a hot work tool steel fabricated by additive manufacturing. Mater Sci Eng A 2019;753:109–21.

https://doi.org/10.1016/j.msea.2019.03.027.
[2] Balaško T, Vončina M, Burja J, Batič BŠ, Medved J. High-temperature oxidation behaviour of aisi h11 tool steel. Metals (Basel) 2021;11. https://doi.org/10.3390/met11050758.
[3] Amorim FL, Stedile LJ, Torres RD, Soares PC, Henning Laurindo CA. Performance and surface integrity of Ti6Al4V after sinking EDM with special graphite electrodes. J Mater Eng Perform 2014;23:1480–8. https://doi.org/10.1007/s11665-013-0852-0.
[4] Kruth IP, Stevens I, Froyen I, Lauwers I. Study of the White Layer of a Surface Machined by Die-Sinking Electro-Discharge Machining. CIRP Ann - Manuf Technol 1995;44:169–72. https://doi.org/10.1016/S0007-8506(07)62299-9.
[5] Kumar S, Singh R, Batish A, Singh TP, Singh R. Investigating surface properties of cryogenically treated titanium alloys in powder mixed electric discharge machining. J Brazilian Soc Mech Sci Eng 2017;39:2635–48. https://doi.org/10.1007/s40430-016-0639-y.
[6] Talla G, Gangopadhayay S, Biswas CK. State of the art in powder-mixed electric discharge machining: A review. Proc Inst Mech Eng Part B J Eng Manuf 2017;231:2511–26. https://doi.org/10.1177/0954405416634265.
[7] Jadam T, Sahu SK, Datta S, Masanta M. EDM performance of Inconel 718 superalloy: application of multi-walled carbon nanotube (MWCNT) added dielectric media. J Brazilian Soc Mech Sci Eng 2019;41. https://doi.org/10.1007/s40430-019-1813-9.
[8] Erden A, Bilgin S. Role of Impurities in Electric Discharge Machining. Proc Int Mach Tool Des Res Conf 1981:345–50. https://doi.org/10.1007/978-1-349-05861-7_45.
[9] Chen YF, Lin YC. Surface modifications of Al-Zn-Mg alloy using combined EDM with ultrasonic machining and addition of TiC particles into the dielectric. J Mater Process Technol 2009;209:4343–50. https://doi.org/10.1016/j.jmatprotec.2008.11.013.
[10] Tripathy S, Tripathy DK. An approach for increasing the micro-hardness in electrical discharge machining by adding conductive powder to the dielectric. Mater Today Proc 2017;4:1215–24. https://doi.org/10.1016/j.matpr.2017.01.140.
[11] Le VT. Influence of Processing Parameters on Surface Properties of SKD61 Steel Processed by Powder Mixed Electrical Discharge Machining. J Mater Eng Perform 2021;30:3003–23. https://doi.org/10.1007/s11665-021-05584-9.
[12] Le VT. The evaluation of machining performances and recast layer properties of AISI H13 steel processed by tungsten carbide powder mixed EDM process in the semi-finishing process. Mach Sci Technol 2022;26, no. 3,:428–59. https://doi.org/10.1080/10910344.2022.2129983.
[13] Schubert A, Bui VD, Schaarschmidt I, Berger T, Martin A. Developments in Powder Mixed EDM and its perspective Application for targeted Surface Modification. Procedia CIRP 2022;113:100–19. https://doi.org/10.1016/j.procir.2022.09.134.
[14] Kumar S, Batra U. Surface modification of die steel materials by EDM method using tungsten powder-mixed dielectric. J Manuf Process 2012;14:35–40. https://doi.org/10.1016/j.jmapro.2011.09.002.
[15] Liew PJ, Yap CY, Nurlishafiqa Z, Othman IS, Chang SY, Toibah AR, et al. Material deposition on aluminium by Electrical discharge coating (Edc) with a tungsten powder suspension. J Adv Manuf Technol 2018;12:133–45.
[16] Singh KJ. Powder mixed electric discharge machining of high-speed steel T1 grade. Multidiscip Model Mater Struct 2019;15:699–713. https://doi.org/10.1108/mmms-03-2018-0039.
[17] Le VT, Hoang L, Ghazali MF, Le VT, Do MT, Nguyen TT, et al. Optimization and comparison of machining characteristics of SKD61 steel in powder-mixed EDM process by TOPSIS and desirability approach. Int J Adv Manuf Technol 2024;130:403–24. https://doi.org/10.1007/s00170-023-12680-8.
[18] Van Tao L, Tien Long B, Thi Hong Minh N, Tien Dung H, Van Thuc D, Hoang Cuong P. Prediction of machining performances in powder mixed electro-discharge machining to process skd61 steel by response surface methodology. Transp Commun Sci J 2024;75:1617–30. https://doi.org/10.47869/tcsj.75.4.12.
[19], et al. Modeling, impact evaluation, and optimization of machining performances of heat-treated SKD61 steel in a tungsten powder alloy mixed EDM process via the RSM-GRA methodology. Sci Technol Dev J 2023;26:3150–60. https://doi.org/10.32508/stdj.v26i4.4222.

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