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Experimental investigation of electrode wear and rapidly re-solidified layer thickness in T90Mn2W50Cr45

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1. Introduction

This paper presents the relevance of standard Response surface methodology (RSM) for studying the effect of Electrode Wear (EW) and Rapidly Re-solidified Layer Thickness (RRLT) in the tool steel of T90Mn2W50Cr45 used in electrical discharge machining process. The process parameters Pulse on time, pulse off time, and pulse current were altered in the experiment. The Response surface methodology (RSM) is used for developing a mathematical model for the Electrode Wear and Rapidly Re-solidified Layer Thickness. The data's obtained for Central Composite Rotatable Design (CCRD) has been used in mathematical model. The end result of Analysis of Variance (ANOVA) has been applied to verify the lack of fit and capability of the built-up models. The predicted and experimental values were quite close, which indicates the developed model can be effectively used to predict the Electrode Wear and Rapidly Re-solidified Layer Thickness in the machining of tool steel of T90Mn2W50Cr45.

Electrical discharge machining (EDM) has been established to be the most feasible electro-thermal process along with the further non-traditional machining processes. The requirements of the present-day product manufacturing industries for machining any category of electrically conductive work, irrespective of its mechanical properties with the extent of achieving essential shape and size with superior productivity, better surface finish characteristics, and better dimensional accuracy features at reasonably reduced costs. The cutting and grinding processes which are required much harder tool or abrasive tool to machining the soft work material.

The EDM process utilizes electrical sparks or thermal energy to erode the redundant work material and create the desired shape. These sparks create craters and the recast layer on the surface of the EDM work piece. The EDM has been extensively functional in modern metal industry for producing complex cavities in moulds and dies, which are complicated to manufacture by conventional machining [1].The variations of geometrical tool wear characteristics and machining performance shown that the machining parameters and dielectric flushing conditions had a large effect on geometric tool wear [2]. Modelling and analysis of the rapidly re-solidified layer of spheroid graphite cast iron on the EDM process using the response surface methodology.

The conclusions reveal that the quantity and area fraction of graphite particle are the most influential factor on the layer thickness and ridge density [3]. The potential difference is measured at the end of the discharge to avoid the influence of the discharge noise. The experimental results showed that a better sensitivity and resolution can be obtained when using the voltage peak value which appears at the end of discharge compared with the method [4]. The metallographic of white layer, which is upper recast layer of heat affected region, in the die skinning EDM.

The obtained consequences indicated that the micro cracks were created making a corner to the machined surface and the dendrites were oblique in the route of the maximum cooling gradient [5]. Analysis the surface integrity of steel in the EDM process rising of pulse energy in machining determine the increase in arbitrary overlapping surface craters, the density, and penetration depth of the cracks in the rapidly re-solidified layer [6]. That deals the increase in pulse duration effect results in an increase in surface roughness, depth of surface micro cracks and depth of heat affected zones. It facilitates the relevance of fine cutting condition beside with lower pulse duration resulting in a better surface geometry [7].

The cooling and solidification at the top surface of the work piece, they analyzed the pock marks, globules, cracks and micro cracks, whose thickness and density depends on the process conditions [8]. Determine the deficiency of machining accuracy due to the deposit of molten metal on the work piece surface in the EDM process [9]. The combined both copper and brass electrodes in the EDM process the electrode erosion rate and electrode wear rate with increasing pulse current were analyzed [10]. The effects of pulse on time, pulse current, and their interaction on the electrode wear using the using statistical analysis, analysis of variance and regression analysis [11]. Empirical and analytical methods for qualitative relationships between the EDM process parameters namely, current and pulse on time and the resulting thickness of the white layer [12].

2. Experimental procedure

The experiments were design based on five level factorial central composite rotatable designs with full replications. These experiments were conducted as per design matrix using EDM machine (Make: EMS 5030 Massive Engineering Private Limited, India). The dielectric fluids are used as kerosene. The work piece material was chosen as a T90Mn2W50Cr45. The chemical composition of the T90Mn2W50Cr45 material is given in Table 1.

Table 1

Chemical composition of test specimen (wt %)

Constituent	C	Mn	Si	S	P	Cr	V	W
Composition (%)	0.90	1.50	0.30	0.025	0.025	0.50	0.25	0.50

The EDM machine prepared of copper electrode materials with 10×30×30 mm^3 in dimensions. The response of rapidly Re-solidified layer thickness was measured by using a zoom microscope. The Electrode wear was calculated by the following formula

$$EW = (W_i - W_f) / t \quad \text{mg/min}$$

where W_i are the before machining weights of electrode material and W_f are the after machining weight of the electrode material, respectively, and 't' is the machining duration time. The electrodes materials were weigh by an electronic weighing machine. The independently controllable process parameters were identified; they are pulse on time (t_{on}), pulse off time (t_{off}) and pulse current (I) were changed during the test on the experimental design. Trial runs were conducted by varying one of the process parameters at a time while keeping the rest of them at constant value. The upper limit of a factor was coded as +1.682 and its lower limit as −1.682, the coded values of the intermediate Zlevels being calculated from the relationship $X_i = 1.682\,[2X - (X_{max} + X_{min})] / (X_{max} - X_{min})]$, where X_i is the required coded value of a variable X and X is any value of the variable from X_{min} to X_{max}; X_{min} is the lower level of the variable; X_{max} is the upper level of the variable. The selected values of the process parameters together with their units and notations are given in Table 2. A three factor, five level central composite experimental designs with six centre points shown in Table 3 was selected to conduct the experiments consisting of 20 sets of coded conditions.

Table 2

Process variables and their limits

Parameters	Symbol	Unit	Notation	Factor Levels				
				-1.682	-1	0	1	1.682
Pulse on time	X_1	μs	t_{on}	27	42	63	84	99
Pulse off time	X_2	μs	t_{off}	2	3	4.5	6	7
Pulse current	X_3	A	I	3	5	9	12	15

The design matrix comprises a full replication factorial design 2^3 plus six star points and six centre points. All EDM variables at the intermediate level (0) constitute the centre points while the combinations at either it's lowest (-1.682) or highest (+1.682) value with the other two variables at the intermediate levels constituting the star points. Thus the 20 experimental runs allowed the estimation of the linear, quadratic, and two-way interactive effects of the process variables on the electrode wear and rapidly Re-solidified layer thickness. Twenty experimental runs were conducted as per the design matrix at random to avoid any systematic error creeping into the system.

The Pulse on time (t_{on}), pulse off time (t_{off}) and pulse current (I) was independent variables studied to predict y responses (Electrode Wear & Rapidly Re-solidified Layer Thickness) the independent variables and their levels for the central composite rotatable designs used in this study are shown in Table 3. In this table, for experimental runs 15 to 20, even through conditions remain the same, the responses vary slightly. This is due to the effect of unknown and unpredictable variables. To account for the impact of these unknown factors on the response, replicated runs (15-20) were included in the design matrix. The response function representing electrode wear and rapidly re-solidified layer thickness can be expressed

$$Y = f(X_1, X_2, X_3 \ldots,) \tag{1}$$

Y is the response e.g. electrode wear and rapidly re-solidified layer thickness etc, X_1 is Pulse on time, (μs); X_2 is Pulse off time, (μs); X_3 is Pulse current, (A).The second-order polynomial (regression) equation used to represent the response surface for three factors could be expressed as given below

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_{11}X_1^2 + b_{22}X_2^2 + \\ + b_{33}X_3^2 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3 \tag{2}$$

where b_0 is the free term of the regression equation, the coefficients b_1, b_2 and b_3 were linear conditions, the coefficients b_{11}, b_{22} and b_{33} are the quadratic conditions and the coefficients b_{12}, b_{13} and b_{23} are the interaction conditions. Evaluation of coefficients of the model values of the coefficients of the above polynomial were calculated with the help of statistical software.

The predictable coefficients obtained above were used to create the model for the response parameter. The adequacy of the developed model was tested by means of using the analysis of variance technique which is presented in Table 4 and 5. It is found that calculated F ratios were larger than the tabulated values with the 95% of confidence level: hence the model is considered to be adequate.

The criterion that is commonly used to illustrate the adequacy of a fitted regression model is the coefficient of determination (R^2) and adjusted R^2. For the developed models, for the calculated R^2 and adjusted R^2 values are provided in Table 4 and 5. These values indicate that the regression model is quite adequate.

Table 3

Design matrix with its experimental results and predicted model value

S.No.	Matrix design			EW (mg/min)		RRLT (µs)	
	t_{on} (µs)	t_{off} (µs)	*I* (A)	Observed	Predicted	Observed	Predicted
1	1	-1	1	8.24	8.02	38.9	39.5
2	1	1	-1	2.4	2.35	16.62	16.35
3	1	1	1	7.25	7.04	38.5	39.5
4	-1	-1	-1	1.96	1.87	14	14.75
5	-1	1	1	7.42	7.18	30.00	30.45
6	-1	-1	1	7.45	7.2	30.5	31.45
7	1	-1	-1	3.28	3.22	16.2	16.4
8	-1	1	-1	2.05	1.97	15.75	16.5
9	0	0	1.682	10.35	10.7	48.62	48.5
10	0	1.682	0	4.24	4.49	23.25	24.7
11	-1.682	0	0	3.85	4.1	19.65	19.8
12	0	0	-1.682	1.65	1.74	13.62	13.65
13	0	-1.682	0	4.98	5.25	24.75	25.5
14	1.682	0	0	4.82	5.06	26.72	27.25
15	0	0	0	5.08	5.18	21.45	21.52
16	0	0	0	5.14	5.24	21.56	21.59
17	0	0	0	5.17	5.26	21.48	21.44
18	0	0	0	5.20	5.29	21.58	21.53
19	0	0	0	5.22	5.16	21.61	21.56
20	0	0	0	5.11	5.19	21.52	21.54

Table 4

ANOVA table for testing electrode wear

Source	DF	SS	MS	F	P
Model	9	96.275	10.697	174.25	0.000
X_1(µs)	1	1.126	1.126	18.34	0.001*
X_2(µs)	1	0.683	0.683	11.12	0.002*
X_3(A)	1	90.69	90.69	1477.03	0.004*
X_1^2	1	0.679	0.679	11.05	0.02*
X_2^2	1	0.219	0.219	3.56	0.244
X_3^2	1	2.268	2.268	36.94	0.000*
X_1X_2	1	0.466	0.466	7.589	0.02*
X_1X_3	1	0.137	0.137	2.231	0.166
X_2X_3	1	0.006	0.006	0.097	0.003*
Residual error	10	0.614	0.0614	-	-
Pure error	5	0	0	-	-
Total	19	96.889	-	-	-

R^2 = 0.994; R^2 (Adj) = 0.988; * Significant
DF – degree of freedom; *SS* – sum of squares; *MS* – mean sum of squares
F – calculated '*F*' ratio; *P*- probability.

Table 5

ANOVA table for testing rapidly re-solidified layer thickness

Source	DF	SS	MS	F	P
Model	9	1616.57	179.62	40.94	0.000
X_1 (μs)	1	131.16	131.16	29.87	0.284
X_2 (μs)	1	0.35	0.35	0.078	0.015*
X_3 (A)	1	1310.17	1310.17	298.44	0.021*
X_1^2	1	2.54	2.54	0.578	0.934
X_2^2	1	33.11	33.11	7.54	0.011*
X_3^2	1	56.12	56.12	12.78	0.005*
X_1X_2	1	0.25	0.25	0.056	0.815
X_1X_3	1	78.11	78.11	17.79	0.002*
X_2X_3	1	4.78	4.78	1.088	0.321
Residual error	10	43.87	43.87	4.387	-
Pure error	5	0	0	0	-
Total	19	1660.45	-	-	-

R^2 = 0.974; R^2 (Adj) = 0.950; * significant
DF – degree of freedom; *SS* – sum of squares; *MS* – mean sum of squares
F – calculated '*F*' ratio; *P*- probability.

The value of the regression coefficient indicates to what extents the factor affects the responses. Insignificant coefficients can be eliminated to increase the accuracy of the mathematical model. To achieve this, *t*- test and *F* tests are used. The test of significance was prepared automatically by the statistical software, during backward steps, a variable is uninvolved from the model and throughout forward steps, and a variable is added automatically to the model. After determining the significant coefficients, the final models were constructed. The final mathematical models with parameters in coded from, as determine by the procedure are presented below:

- electrode wear

$$EW = -4.97 + 0.114\,X_1 + 0.708\,X_2 + 0.321\,X_3 - 0.000398\,X_1^2 + 0.0312\,X_3^2 - 0.00766\,X_1X_2 - 0.0054\,X_2X_3 \quad (3)$$

- rapidly re-solidified layer thickness

$$RRLT = 48.7 - 8.71\,X_2 - 3.24\,X_3 + 0.775\,X_2^2 + 0.155\,X_3^2 + 0.147\,X_1X_3 \quad (4)$$

The regression models developed were tested by drawing scatter diagram. A typical scatter diagram for the electrode wear and rapidly re-solidified layer thickness is shown in Fig. 1 and Fig. 2 the experimental values and predicted values of the responses are scattered close to the 45° line, indicating a nearly perfect fit of the developed empirical model.

3. Results and discussions

Figs. 3 and 4 show the effect of the electrode wear and rapidly Re-solidified layer thickness for variables pulse on-time, pulse off-time and pulse current respectively.

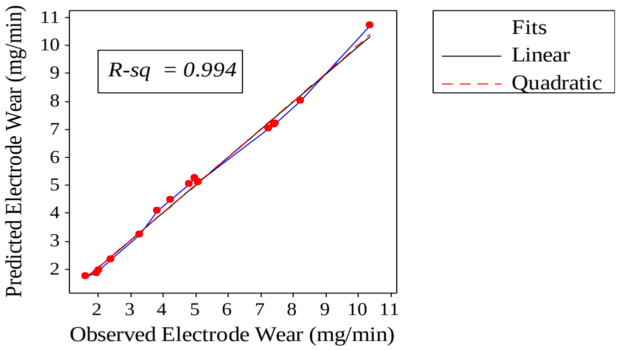


Fig. 1 Comparison of experimental and predicted electrode wear

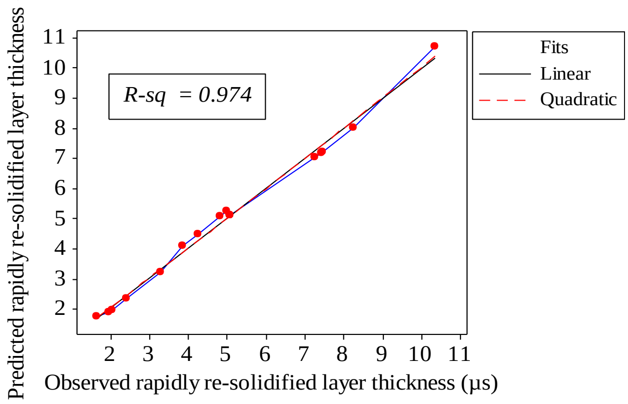


Fig. 2 Comparison of experimental and predicted rapidly re-solidified layer thickness

Electrode wear and rapidly Re-solidified layer thickness are mainly depending on the above said three variables. From the Figs. 3 and 4, it is understood that pulse current is the significant factor on *EW* and *RRLT* because of variation of *EW* and *RRLT* are significant while variation *EW* and *RRLT* are very small for pulse off time. It is due to the fact of increase in pulse current leads to an increase in the rate of heat energy, which causes the electrode wear, and in the rate of melting and evaporation.

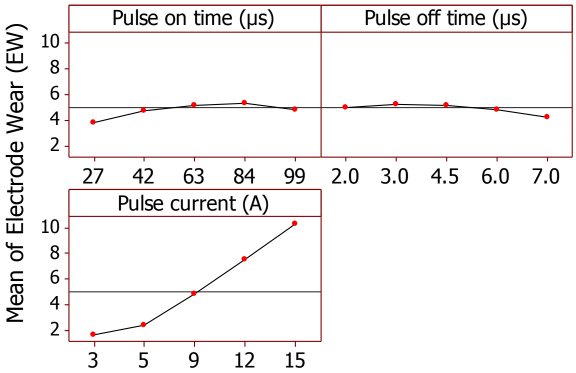


Fig. 3 Effects of the variables on *EW*

Therefore, more heat is transferred into the work piece as the pulse current increases, and the dielectric is continuous not capable to clear away the molten materials, causing to construct upon the surface of the parent material. For the duration of pulse off time, the molten material re-solidified to form re-solidified layer and the thickness of re-solidified layer depends on the volume of molten material. The pulse and pulse interval time are varying linearly. The attached molten work piece material protects the tool electrode surface not in favour of wear.

However, as seen in Fig. 4 the *RRLT* is increased with pulse duration, the combination of high pulse current and low pulse off time leads to better tool wear.

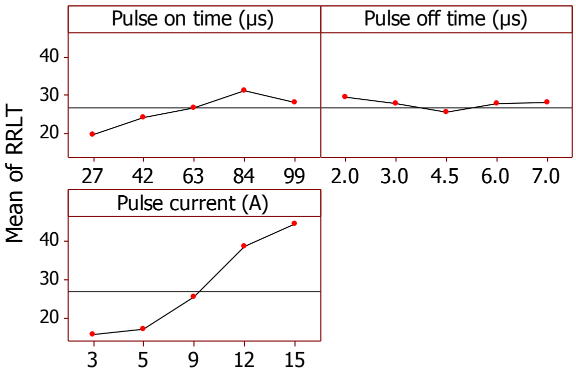
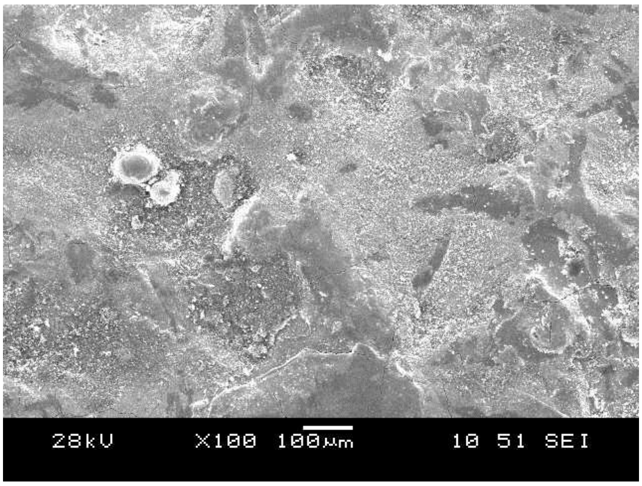
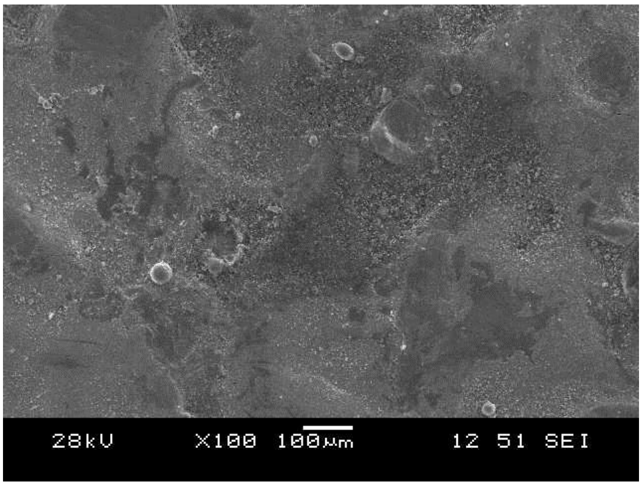


Fig. 4 Effects of the variables on *RRLT*

Fig. 5 shows the SEM landscape of the machined surfaces. Analysis of electrical discharge machining through copper electrode indicates to the molten mass in sheet structure. Fig. 5 shows molten mass comes to establishment surface as chunk, which gets stuck to the surface for the basis of its moderately liquid state. The contour indicates the inaccurate removal, which may be evidence of the way to smooth surface has not occurred due to the larger size of droplets sticking at the surface. The T90Mn2W50Cr45 tool steel consists of singular elements. In order to have higher tool life, it is essential to avoid crack formation in any event, Fig. 5 explains the SEM landscape of the machined surfaces.



a



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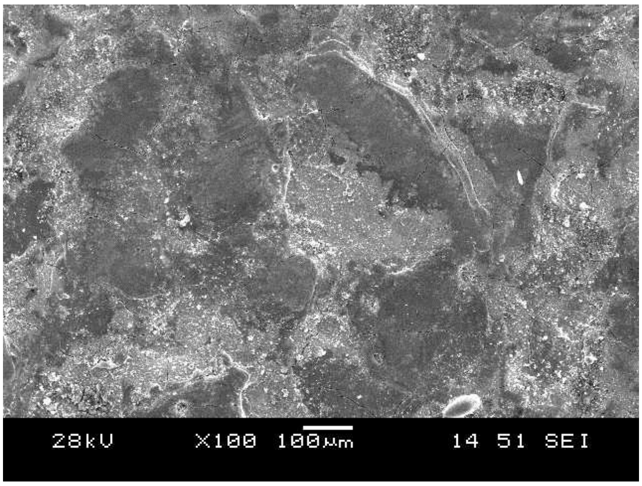

c

Fig. 5 SEM micrograph shows the machined surface: a) 63μs/7μs/9A; b) 42μs/3μs/5A; c) 63μs/4.5μs/15A

An EDM surface comprises of microscopic craters related with the discrete discharges and is essentially of unexciting form. This excellence morphology of the surface, which has undergone in EDM machining, is appropriate to the infinite quantity of heat generated by means of discharges, which cause the vaporization of the accumulation molten metal. The crater size and for this basis surface roughness is related to pulse energy.

The existence of T90Mn2W50Cr45 tool steel material makes it more individual from the surfaces machined with EDM. These material particles do not melt or evaporate throughout the discharge. Their existence alters the gap condition in addition to the flexibility of the molten T90Mn2W50Cr45.

Fig. 5 shows that material particles possibly will be the particles scarlet deposited on the machined surfaces at the ending of the discharge or these particles could be protruded on the surfaces in view of the fact that they were not displaced at some stage in the machining process. Figs. 6 and 7 represents the response surface for the electrode wear and rapidly re-solidified layer thickness response obtained for the regression model. Note that the EW and RRLT tend to significantly increase with a combination of pulse current and pulse on time. Electrodes wear increases with a combination of high pulse current levels and low pulse on time. Otherwise, when a conservative electrode is suggested a combination of high value of pulse current level must be accompanied by low pulse-on time. In addition for low pulse current levels, the electrode wear does not vary as much with pulse on time as it does for high pulse current levels.

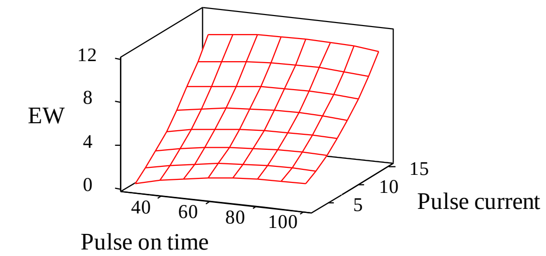

Fig. 6 Surface plot of electrode wear

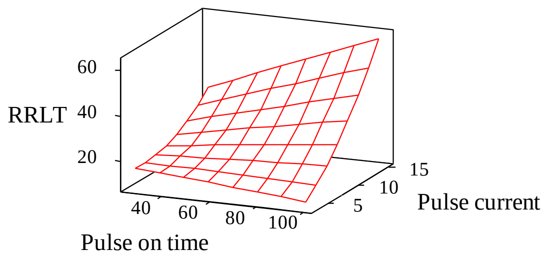

Fig. 7 Surface plot of rapidly re-solidified layer thickness

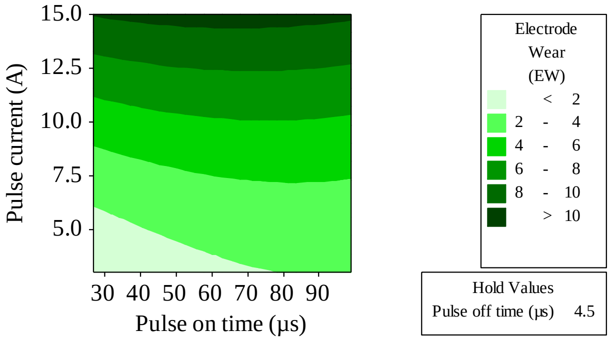

Fig. 8 Contour plot of electrode wear

Fig. 8 and 9 shows that the deviation curve has the contour to denote the pulse current and pulse on time interaction. In addition the twisted plane shown in figure is representative of a typical model with interaction. The contour plots after such useful information that is desirable. Electrode wear and rapidly re-solidified layer thickness response might easily be obtained by searching a direction of improvement.

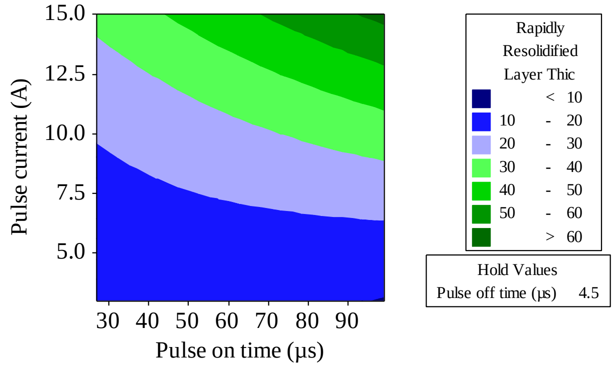

Fig. 9 Contour plot of rapidly re-solidified layer thickness

4. Conclusion

The experiments conducted using Design of experiments were applied to develop regression models using response surface methodology to predict the electrode wear and rapidly re-solidified layer thickness on T90Mn2W50Cr45 materials.

In these experiments, the pulse current has established the nearly all considerable factor performance on both electrode wear and rapidly Re-solidified layer thickness, by the identical time of pulse off time on both responses. The pulse interval time increases the pulse current of T90Mn2W50Cr45 materials.

The machining parameter on the electrode wear and rapidly re-solidified layer thickness has been evaluated using response surface methodology. The most excellent possible machining conditions to make illumination of the electrode wear have been considered.

The elevated discharge current, copper electrode is the evidence for uppermost material removal rate. The scanning electrode machining of electrical discharge machining surface indicates that molten mass has been detached from the surface indicated as ligaments and mass and also as chunks, which are obtained at stuck to surface, appropriate to molten situation.

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T90Mn2W50Cr45 ELEKTRODO DILIMO IR GREITAI KIETĖJANČIO SLUOKSNIO EKSPERIMENTINIS TYRIMAS

R e z i u m ė

Straipsnyje tiriama, ar paviršiaus atsako vertinimo metodologijos standartas tinka elektrodo dilimui ir elektrokibirkštiniame apdirbimo procese naudojamo įrankinio plieno T90Mn2W50Cr45 greitai kietėjančio sluoksnio storiui nustatyti. Tokie proceso parametrai, kaip įjungimo impulsas, išjungimo impulsas ir srovės impulsas eksperimentuojant kartojosi. Paviršiaus atsako metodologija taikoma elektrodo dilimo ir greitai kietėjančio sluoksnio storio matematiniam modeliui sudaryti. Gauti centrinio kompozitų pokyčio dizaino duomenys buvo panaudoti matematiniame modelyje. Galutinis variantų analizės (ANOVA) rezultatas buvo pritaikytas standarto tinkamumui ir sukurtų modelių galimybėms patikrinti. Numatytos ir eksperimentinės vertės pasirodė artimos toms, kurios rodo, kad sukurtąjį modelį galima efektyviai naudoti elektrodo dilimui ir greitai kietėjančio sluoksnio storiui apdirbant įrankinį plieną T90Mn2W50Cr45 numatyti.

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EXPERIMENTAL INVESTIGATION OF ELECTRODE WEAR AND RAPIDLY RE-SOLIDIFIED LAYER THICKNESS IN T90Mn2W50Cr45

S u m m a r y

This paper presents the relevance of standard Response surface methodology (RSM) for studying the effect of Electrode Wear (EW) and Rapidly Re-solidified Layer Thickness (RRLT) in the tool steel of T90Mn2W50Cr45 used in electrical discharge machining process. The process parameters Pulse on time, pulse off time, and pulse current were altered in the experiment. The Response surface methodology (RSM) is used for developing a mathematical model for the Electrode Wear and Rapidly Re-solidified Layer Thickness. The data obtained for Central Composite Rotatable Design (CCRD) has been used in mathematical model. The end result of Analysis of Variance (ANOVA) has been applied to verify the lack of fit and capability of the built-up models. The predicted and experimental values were quite close, which indicates that the developed model can be effectively used to predict the Electrode Wear and Rapidly Re-solidified Layer Thickness in the machining of tool steel of T90Mn2W50Cr45.

Keywords: Electric discharge machining, response surface methodology, central composite rotatable design, analysis of variance, electrode wear, rapidly re-solidified layer thickness.

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