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Simultaneous optimization of WEDM parameters for CPOH steel by central composite design

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This study aims to determine the appropriate parameter levels during cutting process of CPOH steel by using Cut 300, a new wire erosion machine, in a company operating in defense and aviation sector. In the study, CCD (central composite design) which is the frequently used type of RSM (response surface methodology) has been used for the optimization of SR (surface roughness) and CT (cutting time). According to the literature, it has been seen that the process parameters that may be effective in optimization are current, T_{on}, T_{off} and WFR (wire feed rate). Parameters having significant effect for response variables has been determined by ANOVA. Prediction models has been built by regression analysis and desirability function was used for simultaneous optimization of all responses. Optimized parameter levels has been determined as current 22.69 (*Amp*), T_{on} 0.8 (µs), T_{off} 8.01 (µs) and 22.60 (mm /min) WFR. After conducting confirmation tests the responses Ra, Rz and CT has been obtained 0.38 (µ), 2.23 (µ) and 10.84 (min), respectively. The results fall into the prediction interval ensure the model validation.

Keywords: Electro-discharge, Central composite design, Precision, Cutting, Optimization, CPOH steel

1 Introduction

In order to meet the ever-growing needs of the industry, both new types of materials and new processing techniques have been developed. The properties of the previous materials such as cutting-breaking strength and abrasion resistance are always carried a step forward and new generation steels are developed. These new generation steels have disadvantages of processing despite acquisitions they gained. In cases where classical machining remains insufficient, processing techniques like WEDM-"Wire Electrical Discharge Machining" are used.

In the manufacturing industry, the most important process output in the processing of sheet metal molds by machining is SR. During machining, complete and reliable data are vital to achieve the desired results. WEDM production method has emerged as a popular and non-traditional production method. With this technique, the conductive materials can be processed even though they are grift and complex shaped and rigid[1].

WEDM's entry time to market goes back to the 1970s. With the rapid development of the industry, materials with high hardness and strength have been developed. It is very difficult to process such materials with conventional manufacturing methods. It is possible to process the materials with both high hardness and complex shaped via WEDM[2]. WEDM uses electro thermal energy in conductive materials. During the process, when the electrons erosion the material by wire, there is dielectric fluid in the environment. The cut-off parts of the workpiece are very close to the wire, which are exposed to sparks and molten metals which have been removed from the surface by melting. Therefore, the material properties of the melted region are important characteristics[3]. The WEDM method is a high-cost processing technique in addition to high technical requirements mentioned. Therefore, the work piece cut by the machine is requested to be cut as soon as possible. In addition, the cut work piece is expected to be of high accuracy and good surface quality[4].

The processing of CPOH steel, which is used in cutting, bending and forming processes in precision cutting molds, by using WEDM method is discussed in this study. CPOH steel is a cold work tool steel which is difficult to process due to its superior properties. For this reason, WEDM technique has been chosen due to the fact that both the profiles are grift and the requirements for high precision machining.

RSM is a technique used to determine variable values that may affect process performance by

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systematically changing the values of controllable variables affecting the related quality characteristics of the process. It is quite effective in seeing the effect of factors at the same time, comprehending the interactions between factors, searching the factors which affect the reliability/quality and establishing the hypothetical model[5]. The experimental design especially provides highly efficient and cost-effective solutions for the processes with high costs and long processing times.

Literature research is included and information about similar studies and methods are given as follows;

Conde *et al.*[6] suggested an approach based on the Elman-based LRNN method. The average deviation between the actual values and the estimations was less than 6 µm, which is a good performance indicator. Then, with the help of a SA- "simulated annealing" algorithm, radial deviations emerging due to wire deformation are minimized. Validation of the model was made under industrial conditions and it was seen that the suggested method gave successful solutions especially when wire deformation was high.

Choudhary *et al.*[7] investigated the effect of cryptogenic treated wire electrode and the copper electrode which hasn't treated with cryptogenic process copper electrode on SR and processing performance in the treatment of Hastelloy C-4 used in space and aviation. By analyzing the experiment results, it was found that the current was the most effective factor for SR and it was followed by T_{on}, electrode type and T_{off}. This study indicates that the wire treated with cryptogenic process improves SR compared to untreated wire electrode.

Jafari *et al.*[8] examined the effect of micro-WEDM method on the SR of the metal-based micro-channel heat transmitter. The parameter which has critical effect on SR was discharge current.

Kumar *et al.*[9] investigated optimum machine parameters for the WEDM technique for Nimonic-90 material. Nimonic-90 has been chosen because this is a material frequently used in the space and aviation industry. By using RSM; cutting speed, SR and ROC- "radial overcut" performance indicators have been optimized. For all three responses, quadratic models were suggested and in accordance with the results of variance analysis. it has been seen that peak current, T_{on}, T_{off}, and SV- "servo voltage" were effective variables on cutting rate and SR, while peak current, T_{on} and SV are extremely effective on ROC.

Goyal[10] investigated the effect of process parameters on MRR- "material removal rate" and SR during the cutting process of Inconel 625 material with WEDM. Material thickness and wire diameter were kept constant. At the end of the analysis, T_{on}, tool electrode and current intensity parameters have a significant effect on performance indicators. Linear regression equations were also used for MRR and SR response variables.

Yang *et al.*[11] studied on the optimization of WEDM parameters used in the processing Inconel 718 material with L9 Taguchi orthogonal array. The performance characteristics are to maximize the MRR and to achieve the lowest SR value. In multi-objective optimization, the Taguchi method was used together with GRA- "Gray Relational Analysis" and better results were obtained for both objectives.

Kandpal *et al.*[12] identified the performance characteristics of the aluminum 6061 alloy material in the EDM machining method as the MRR, WFR and the overcut of surface topography along the hole cut and SR. Due to the increase in T_{on} and peak current, it has been observed that the values of MRR, tool wear rate, overcut and SR increased. It has been observed that the duty factor had no significant effect on the responses, and it has been understood that a better combination of other factors could reduce electrode wear.

Nayak and Mahapatra[13] used WEDM method for conical cutting from cryo-treated In conel 718 material, it has been determined that traditional Taguchi method has not been successful enough in multi objective optimization and alternative solutions have been produced with heuristic methods. The relationships were determined with ANN model. A good combination of parameters has been suggested by utilizing the bat algorithm for the overall optimization of performance characteristics.

Goswami and Kumar[14] examined SR, MRR and WWR as performance characteristics in cutting Nimonic 80A material with WEDM. The selected levels for the flushing pressure, servo feed and pulse peak voltage were kept constant. It has been seen that all input parameters and interactions have a significant effect on responses. The most effective factors on MRR are T_{on} of 46% and T_{off} with 33% contribution. The peak current and T_{off} were the most effective parameters for wire removal rate and the interaction effect of T_{on} and T_{off} on wire removal rate was seen to be 32.13%.

Aldas *et al.*[15] made the estimation of the SR after processing Dievar hot tool work steel with WEDM by using the ANFIS modeling on the basis of experimental study. Table feed rate, current and T_{on} were selected as independent variables in experimental study and modeling. Voltage, refrigerating liquid pressure, wire feed speed, wire tension and wire electrode diameter were kept constant and as performance characteristic, SR was chosen.

Manjaiah *et al.*[4] aimed at optimizing WEDM parameters for $Ti_{50}Ni_{40}Cu_{10}$ material. The electrode type, diameter and the electrical pressure are kept constant. As a result of the analysis, it was seen that peak current, T_{on} and SV had significant effects on MRR and surface finish. T_{off} and WFR parameters were not seen to be effective on responses.

Ikram *et al.*[16] studied on the optimization of 8 control factors by means of D2 die steel over MRR, SR and kerf performance indicators. The fixed parameters are the diameters of wire, the deionized liquid and the type of wire (brass). As a result of the analysis, it can be said that T_{on}, wire tension and open voltage were effective on the SR response variable. T_{on}, wire tension and open voltage were effective on the kerf and T_{on}, open voltage and SV were effective on MRR.

In the study of Kumar *et al.*[17] four controllable machining parameters, viz. gap voltage (A), current (Ip), duty cycle (C) and pulse on time (T_{on}) have been chosen to ascertain the electrode wear rate (EWR) and surface roughness (SR) of AISI 420material with copper electrode. L16 orthogonal array (OA) was used. During machining of AISI420, the highest influencing factor in EWR is IP and least is C. Similarly, for SR T_{on} is most and C is least significant factor.

The methods used in the aforementioned publications, selected factors and performance indicators are summarized in Table 1.

To the best of our knowledge, CPOH steel and Agie Charmilles Cut 300 machine which is a new generation of wire erosion machine were handled for the first time in the optimization procedure by this study. This machine ensures to protect itself according to the conditions with the help of servo

Table 1 — Literature review.

Reference No.	Solution Methods	Factors	Performance Characteristics
17	Taguchi L16	gap voltage (A), current (Ip), duty cycle (C), pulse on time (T_{on})	Electrode wear rate, SR
6	LRNN SA	Thickness and radius in the WEDM samples, Height, Off-time, Current intensity, Open-circuit voltage, Dielectric pressure, Wire tension, Offset	Radial deviations due to wire deformations
11	Taguchi L9 GRA	Discharge time, Machining voltage, Rest time, SV	SR, MRR
12	Taguchi L27	Peak current, T_{on}, Duty factor	MRR, Electrode wear rate, SR, Over cut
8	Taguchi L25 ANN	T_{on}, T_{off}, Discharge current, Peak voltage, Spark time, Wire speed	SR parameters (Ra, Rz, Rv, and Sm)
	CCD	Discharge current, T_{on}, T_{off}, SV	ROC, Cutting speed, SR
10	Taguchi L18	Tool electrode, Current intensity, T_{on}, T_{off} , Wire feed, Wire tension	MRR, SR
7	Taguchi L18	Tool electrode, Current, T_{on}, T_{off}	SR
13	ANN Bat Algorithm Taguchi L27	Part thickness, Taper angle, Pulse duration, Discharge current, Wire speed, Wire tension	Angular error, SR, Cutting speed
14	Taguchi L27 GRA	T_{on} , T_{off}, Peak current, Wire feed, Wire tension, Spark gap set voltage	MRR, WRR
15	ANFIS	Feed rate, Current, , T_{on}	SR
4	Taguchi L18	Peak current, T_{on}, T_{off}, SV, WFR	SR, MRR
16	Taguchi L18	Wire feed velocity, Dielectric pressure, T_{on},T_{off}, Open voltage, Wire tension, SV, Material thickness	MRR, SR, Kerf
18	Taguchi L16	T_{on}, Wire tension, Delay time, Wire feed speed, Ignition current intensity	MRR, SR, WWR
19	Taguchi L18	Pulse-generating circuit, Conductivity of dielectric, Resistance in the circuit, Capacitance in the circuit, Applied voltage, Feed rate of the table, T_{off} , Error	SR

Table 2 ─ Chemical component of CPOH material used in the experiments.

%Base	%C	%Cr	%Mo	%V	%P	%S	%Fe
Fe	0.99	7.96	2.54	0.29	0.021	0.011	Rest

motor, generator and voltage adjustment technologies. It was aimed to optimize the parameters related to the aforementioned machine for different objectives and to create a substructure study for the firms which are using WEDM. As well as Ra and Rz (performance indicators to analyze the SR), the CT is also determined as another performance indicator for the first time due to the high processing costs and machine hourly rates. Minimizing the CT ensures lower processing costs and higher energy saving. On the other hand, the studies which combine parameter optimization of WEDM and RSM are quite rare in the literature. The methodology mentioned in this study was applied for a firm in defense industry. Consequently, this methodology and optimum conditions can be used for any firm considering CPOH steel that is processing on the Agie Charmilles Cut 300 machine.

In the materials and methods section, the subjects such as preparation of samples, experimental conditions, determination of process parameters and measurement of response variables are discussed. In the following section, RSM and CCD, the experimental plans, selection of regression models for response variables and simultaneous optimization are discussed. In the last section, comments on the results and recommendations for further studies are included.

2 Materials and Methods

In this study, it was studied on CPOH steel used in cutting, bending and forming processes in precise cutting molds by using WEDM. SR (Ra and Rz) and CT were determined as the most important variables.

2.1 Experimental conditions and tests

The steel to be used in the experiments was carried out through a number of stages before the experiments were done. The chemical composition of the material is given in Table 2.

The material used for the tests is in the sizes of 20mmx420mmx3450 mm. The raw material is supplied in soft annealed and 250 HB hardness. CPOH is a cold work tool steel with high molybdenum content. Its toughness is better than 1.2379 steel. The maximum hardness value with tempering at 520-560 ^{0}C is approximately 63 HRc.

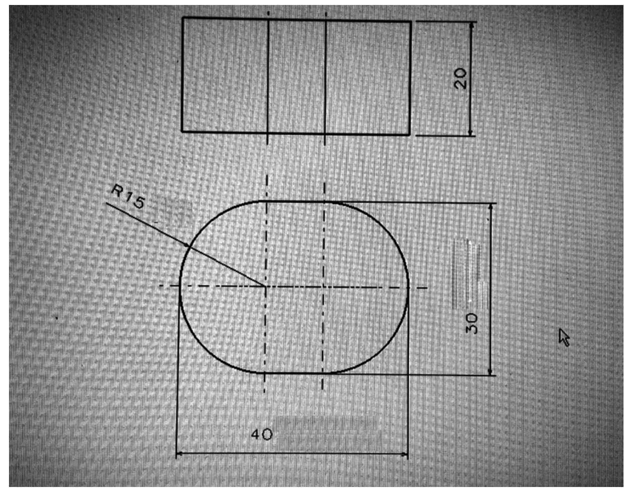

Fig. 1 — Sample form used in wire erosion cutting .

The surface of the material undergoing pre-treatment was smoothed first by heat treatment and then grinding. The reason of making heat treatment before processing is to prevent the dimensional distortion. In order to process a heat treated material with high accuracy, traditional machining methods are not sufficient and cutting can be made by wire erosion.15.5 kg steel with dimensions of 20mm x 420 mm x 3450 mm is heat treated in vacuum furnace. As a result of the heat treatment, it was hardened to 61-62 HRc. The material was subjected to grinding after heat treatment to eliminate surface irregularities.

The form given in Fig. 1 including both radius and straight cuts have been used. The dimensions of the sample cutting pieces are 30x40x20 mm and they contain R10 form. In the experiments, neutral deionized coolant water and copper coated wire electrode in 0.25 mm diameter were used.

2.2 Process parameters

The most important factors were selected by considering the experiences of the company and the information obtained from the literature.

Current, is the parameter that sets the maximum current value and controls the amount of current applied to the wire electrode. The current value which can be adjusted for the material in 20 mm thickness at the Cut 300 machine ranges from a minimum of 1 ampere to a maximum of 30 amperes. They are raised and lowered by one amperage increments.

T_{on}, increases both SR and surface crack density simultaneously[20]. The smallest T_{on} is 0.05 µs and the maximum T_{on} is 1.05 µs for the material of 20 mm. An increase of the segments of 0.05 µs is provided.

T_{off} is defined as "the time during which re-ionization of the dielectric take place. An insufficient off time can lead to erratic cycling and retraction of the advancing servo thereby slowing down the operation cycle"[21]. The minimum T_{off} that can be set in material of 20 mm is 3.6 µs and the maximum T_{off} is 20 µs. With the 0.1 µs of segments, the increase is provided. If this period is too high, the CT prolongs and high cost occurs. When it is kept too low, the cooling may not occur.

WFR regulates how much or how fast the wire is feed while cutting the workpiece. Minimum WFR of the machine is 1 mm/min and maximum WFR that can be ensured is 30 mm/min. It is achieved an increase of 0.2 of segments.

The factors and their levels used in the experimental design are given in Table 3.

Table 3 — Factors and their levels.

Factors	Coded levels				
	-α	Low	Center	High	+α
	-2	-1	0	+1	+2
A:Current (A)	1	8.25	15.5	22.75	30
B:Puls on-time(µs)	0.05	0.3	0.55	0.8	1.05
C:Puls off-time (µs)	3.6	7.7	11.8	15.9	20
D:Wire feed rate (mm/min)	1	8.25	15.5	22.75	30

Fig. 2 — Positioning the part and its fixture.

2.3 Response variables

SR has been chosen as the first performance characteristic since its importance. The SR performance character was measured as Ra and Rz. The SR device was measured with the MarSurf M 300 by a fixture tightening the part. Besides, due to the fact that wire erosion labor costs are higher than the costs of the turning and grinding labor that are the traditional production methods, the CT has been chosen as another performance characteristic.

Before measuring the SR of the part, the surface which was cut by wire erosion was hold by side and brought to the top side. Then, it was tightened with an apparatus and set to the position seen in the figure. The reason for doing this is to prevent the part from vibration, to be measured incorrectly and the difference between the measurements. The apparatus and the position where the part is positioned is given in Fig. 2. The measurements were made in the mode of Standard ISO Lt: 1.75 (0.250 x 5).

2.4 Experimental design and modelling

RSM is a set of mathematical and statistical techniques used in modeling and analyzing the performance characteristics that are affected by many variables and which are desired to be optimized[5].In many RSM problems, the relationship between performance characteristics and independent variables is unknown. In this case, the first thing to be done is to determine the convergence between independent variables and performance characteristics[22]. Generally, it is required to test the polynomial changes of the low and high levels of the independent variables on the dependent variable. If the performance characteristic of the system can be explained as a linear function of the independent variable, first-order polynomial equation can be used as a model. First-order polynomial models remain insufficient to determine the curvature of the response surface. If there is a curvature, second order polynomial equations should be used[23-24].

CCD was found by Box and Wilson as an alternative to 3k factorial designs in 1951. The CCD is one of the most common applications of RSM. The CCD experiment strategy consists of 2k factorial points commonly coded as -1 and +1, center points coded as 0, and of axial points at a distance of ±α from the center point. The main effects of the factors in the second order model and the first order interaction effects are obtained from the 2k experiment. The curvature of model is estimated by using center points and the second and higher order effects are estimated by using axial points.

3 Results and Discussion

After cutting processes performed depending on the experimental design, SR (Rz and Ra) and CT measurement results were analyzed with Design Expert.

Table 4 — Experimental design for CCD

Run	*A*	*B*	*C*	*D*	Ra	Rz	Cutting Time
1	-1	-1	-1	-1	4.775	28.395	130.080
2	+1	-1	-1	-1	3.175	18.792	86.080
3	-1	+1	-1	-1	2.602	15.358	70.350
4	+1	+1	-1	-1	1.082	6.503	26.350
5	-1	-1	+1	-1	4.606	27.380	125.430
6	+1	-1	+1	-1	3.317	19.647	90.000
7	-1	+1	+1	-1	2.408	14.191	65.000
8	+1	+1	+1	-1	1.151	7.236	30.455
9	-1	-1	-1	+1	5.152	30.656	140.440
10	+1	-1	-1	+1	1.523	8.886	40.690
11	-1	+1	-1	+1	2.962	17.518	80.245
12	+1	+1	-1	+1	0.372	2.242	10.250
13	-1	-1	+1	+1	4.954	29.469	135.000
14	+1	-1	+1	+1	1.563	9.961	45.620
15	-1	+1	+1	+1	2.783	16.444	75.325
16	+1	+1	+1	+1	0.419	2.259	10.330
17	-2	0	0	0	5.815	34.637	166.152
18	+2	0	0	0	0.960	5.617	30.330
19	0	-2	0	0	5.881	35.031	148.840
20	0	+2	0	0	1.336	8.409	26.936
21	0	0	-2	0	1.793	10.501	48.095
22	0	0	+2	0	1.945	11.412	52.270
23	0	0	0	-2	2.496	15.220	75.185
24	0	0	0	+2	1.321	8.000	35.120
25	0	0	0	0	1.864	10.926	50.040
26	0	0	0	0	1.890	10.859	51.020
27	0	0	0	0	1.848	10.888	52.180
28	0	0	0	0	1.789	10.456	51.780

3.1 Statistical analysis

In our study, CCD by adding axial points on the 2^4 full factorial experimental design is given in Table 4. In this plan; factorial points were represented by experiments no 1 to 16, and the axial points by the experiments no 17 to 24 and the central points by the experiments no 25 to 28. If it is possible to do it in terms of time and cost, experiments for the central points can be repeated more than four times.

3.1.1 Surface roughness (Ra and Rz)

In this study,"A", "B", "C" and "D" denote current, T_{on}, T_{off}, and WFR, respectively. Using the experimental data, ANOVA was done for all performance measures. Quadratic model was best for Ra and Rz. ANOVA results (Table 5) showed that quadratic models were good at explaining the relationships.

As a result of the ANOVA, the terms "A", "B", "D", "AB", "AC", "AD", "BD", "A^2"and "B^2" were found to have a critical effect on Ra. No lack of fit was observed in the model. That the F value of the model is 1901.60 and the p value is <0.05 indicates that H_0 hypothesis in the 5% significance level can be rejected and the model is significant. Considering p values for model terms, it is seen that all of them are <0.05 except C. If several insignificant terms exist in the model, it is required to reduce the model. Here, "A", "B", "D" show the main effects; "AB", "AD", and "BD" show the effects of interaction and "A^2" and "B^2" also show the quadratic effects of the related factors. In addition, it was observed that there was no lack of fit in the model (p = 0.3764).

The model for Ra is given in Eq. (1) for coded levels.

$$\text{Sqrt (Ra)} = 1.36 - 0.37A - 0.31B - 0.1D - 0.028AB + 0.02AC - 0.15AD + 0.02BD + 0.083A^2 + 0.11B^2 \quad \dots (1)$$

The power transformation of square root with lambda 0.5 was found to provide the best fit for all three responses. The coefficient R^2 is defined as "the ratio of the explained variation to the total variation and is a measure of the degree of fit.[25]" The adjusted R^2 = 0.9984 is in reasonable agreement with the predicted R^2 = 0.9974.

Table 5 — ANOVA Table for Ra and Rz.

Source	SS	df	MS	F value	p value
Ra[a]					
Model	6.62	9	0.74	1901.60	<0.0001
A	3.22	1	3.22	8310.32	<0.0001
B	2.36	1	2.36	6100.65	<0.0001
D	0.25	1	0.25	644.65	<0.0001
AB	0.012	1	0.012	31.87	<0.0001
AC	6.506E-003	1	6.506E-003	16.81	0.0007
AD	0.35	1	0.35	901.74	<0.0001
BD	6.548E-003	1	6.548E-003	16.92	0.0007
A^2	0.18	1	0.18	477.61	<0.0001
B^2	0.31	1	0.31	788.02	<0.0001
Residual	6.968E-003	18	3.871E-004		
Lack of Fit	6.219E-003	15	4.146E-004	1.66	0.3764
Pure Error	7.489E-004	3	2.496E-004		
Core Total	6.63	27			
Rz[b]					
Model	39.43	10	3.94	2072.61	<0.0001
A	18.97	1	18.97	9973.77	<0.0001
B	13.96	1	13.96	7336.66	<0.0001
D	1.53	1	1.53	803.66	<0.0001
AB	0.071	1	0.071	37.20	<0.0001
AC	0.051	1	0.051	26.91	<0.0001
AD	2.12	1	2.12	1116.25	<0.0001
BD	0.018	1	0.018	9.63	0.0065
A^2	1.10	1	1.10	579.40	<0.0001
B^2	1.98	1	1.98	1039.27	<0.0001
D^2	7.222E-003	1	7.222E-003	3.80	0.0681
Residual	0.032	17	1.902 E-003		
Lack of Fit	0.029	14	2.069 E-003	1.84	0.3398
Pure Error	3.376E-003	3	1.125 E-003		
Core Total	39.46	27			

[a] R^2= 0.9989 R^2 (adj)=0.9984 Pred. R^2=0.9974
[b] R^2 =0.9992 R^2 (adj)=0.9987 Pred. R^2=0.9979

3-D surface plots for Ra are shown in Fig. 3 (a-c). When the interaction effect plots are examined, the Ra value decreases as the current value increases from 8.25 to 22.75. Ra decreases as the T_{on} increases. The T_{on} seems to have a quadratic effect on the Ra. As the WFR increases, Ra decreases.

For the Rz, a quadratic model was suggested as in Ra, and as a result of the ANOVA, the terms “A”, “B”, “D”, “AB”, “AC”, “AD”, “BD”, “A^2”, “B^2” and “D^2” were found to have a critical effect.

The model of Rz is given in Eq. (2) for coded levels.

$$Sqrt(Rz) = 3.29 - 0.89A - 0.76B - 0.25D - 0.067AB + 0.057AC - 0.36AD + 0.034BD + 0.21A2 + 0.28B2 + 0.017D2 \quad \ldots (2)$$

The effect of other factors on the Rz which is a SR performance indicator was examined by means of graphs. The value of Rz decreases as the current increases. When a single cut is made with good cooling and high current instead of being exposed to continuous current of the same area, fewer craters come out and the SR value is found to be good. While the T_{on} is at its highest level, the Rz takes the lowest value. The quadratic effect of the T_{on} is also critical. Rz takes the lowest value while the WFR is at maximum level.

3.1.2 CT-cutting time

After the ANOVA and regression analysis, a quadratic model was suggested and the lack of fit was seen to be insignificant. As a result of the variance analysis, the terms that were p <0.05 were considered as significant and included in the model. “A”, “B”, and “D” main effects, “AB”, “AC”, “AD”, and “BD” interaction effects and “A^2” and “B^2” quadratic effects

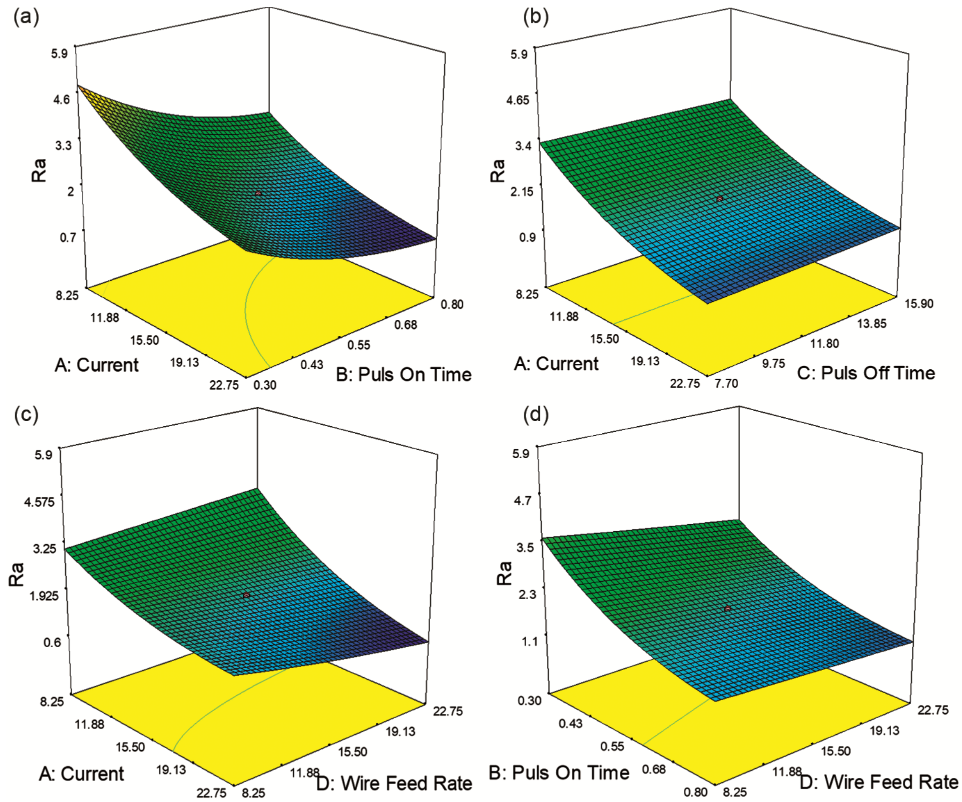

Fig. 3 — (a) Effect of current and T_{on} on Ra at T_{off}=11.80 µs; WFR= 15.5 mm/min, (b) Effect of current and T_{off} on Ra at T_{on}= 0.55 µs; WFR= 15.5 mm/min, (c) Effect of current and WFR on Ra at T_{on}=0.55 µs; T_{off}=11.80 µs, and (d) Effect of T_{on} and WFR on Ra at current= 15.50 Amp µs; T_{off}=11.80 µs.

have a critical impact on 5% significance level. The ANOVA table of the model are given in Table 6.

The equation for CT is given in Eq. (3) for coded levels.

$$\text{Sqrt (CT)} = 7.18 - 1.92A - 1.70B - 0.55D - 0.18AB + 0.13AC - 0.74AD + 0.11BD + 0.51A^2 + 0.38B^2 \quad \ldots (3)$$

Interaction effect of factors on CT is given in Fig. 4 (a-c). When the main effect plots are examined, the CT decreases as the current moves from 8.25 to 22.75. The current has a quadratic effect on the CT. The CT decreases as the T_{on} increases and the lowest CT is seen as the T_{on} is at the level of 0.8. It also decreases as the WFR is moving from 8.25 to 22.75. There is a negative linear relationship between WFR and CT.

"NPP- Normal probability plots of internally studentized residuals is an important diagnostic tool to detect and explain the systematic departures from the assumption"[26] . The NPP of residuals for Ra, Rz and CT are shown in Fig. 5(a-c). According to the figures, the normality assumption was satisfied.

Table 6 — ANOVA Table for cutting time.

Source	SS	df	MS	F value	p value
Model	183.98	9	20.44	700.26	<0.0001
A	88.02	1	88.02	3015.19	<0.0001
B	69.49	1	69.49	2380.48	<0.0001
D	7.38	1	7.38	252.68	<0.0001
AB	0.51	1	0.51	17.30	0.0006
AC	0.26	1	0.26	8.77	0.0084
AD	8.88	1	8.88	304.21	<0.0001
BD	0.18	1	0.18	6.32	0.0217
A^2	6.85	1	6.85	234.75	<0.0001
B^2	3.87	1	3.87	132.62	<0.0001
Residual	0.53	18	0.029		
Lack of Fit	0.51	15	0.034	7.86	0.0575
Pure Error	0.013	3	4.343E-003		
Core Total	184.50	27			
R^2 =0.9972	R^2 (adj)=0.9957		Pred. R^2=0.9926		

3.2 Simultaneous optimization

Optimization is defined by[27] as "the process of either maximizing the functional requirements or minimizing the undesirable effects". In this study, desirability functions are used to simultaneously optimize all the three responses. This approach is "a search-based optimization method which optimizes multiple response variables, individually and

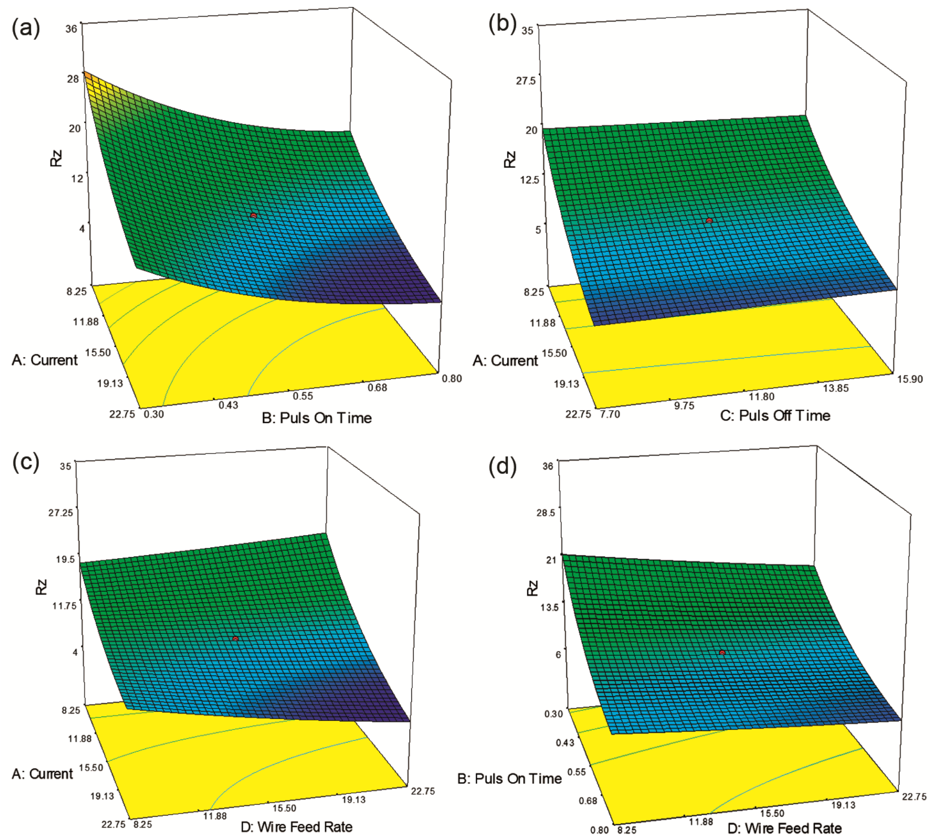

Fig. 4 — (a) Effect of current and T_{on} on cutting time at T_{off}=11.80 µs; WFR= 15.5 mm/min, (b) Effect of current and T_{off} on cutting time at T_{on}= 0.55 µs; WFR= 15.5 mm/min, (c) Effect of current and WFR on cutting time at T_{on}= 0.55 µs; T_{off}=11.80 µs, and (d) Effect of T_{on} and WFR on cutting time at current= 15.50 Amp µs; T_{off}=11.80 µs.

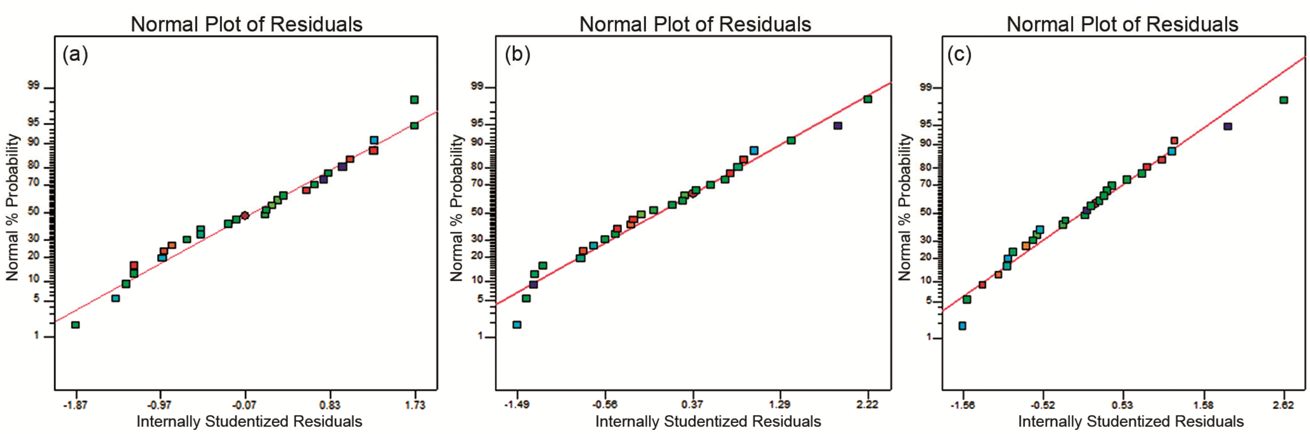

Fig. 5 — Normal probability plots of internally studentized residuals (a) Ra, (b) Rz, and (c) Cutting time.

simultaneously to find the optimum input variable settings"[28-32]

The local optimum solutions are obtained and among the solutions, the solution with the highest desirability value and the lowest Rz, Ra and the CT is appropriate. When the machine set to be 22.69 (Amp) for current value, 0.8 (µs) for T_{on}, 8.01 (µs) T_{off} and 22.60 (mm /min) for WFR, it was estimated to be 0.366 µ for Ra and 2.127 µ for Rz and 9.047 min. for CT.

Since it is known that the factors having the most critical effect are current and T_{on}, the surface graph related to the relevant factors is given in Fig. 6. The desirability value is 1 at the highest level of current

Table 7 — Prediction intervals for responses.

Response	Prediction	95% PI low	95% PI high	Confirmatory Trial
Ra	0.3664	0.31	0.43	0.38
Rz	2.1268	1.82	2.46	2.23
Cutting Time	9.0465	6.68	11.77	10.84

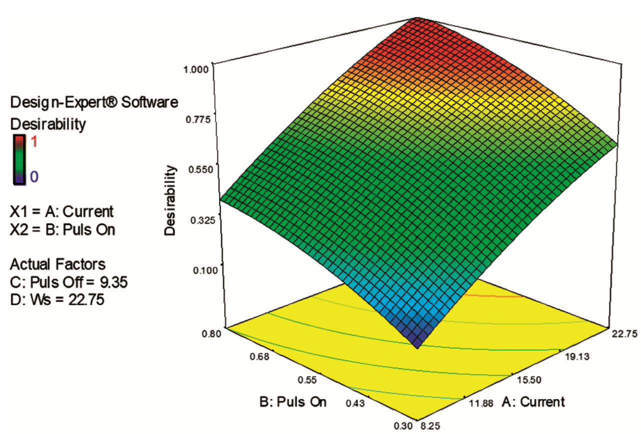

Fig. 6 — Surface graph for desirability value (current and pulse on-time).

and T_{on}. The highest desirability values take place in red zones while the green and blue zones show the lower values of desirability.

For the proposed optimal levels, confirmation experiment is performed. According to the confirmatory results, the values of Ra, Rz and CT are 0.38 μ, 2.23 μ, and 10.84 min, respectively as shown in Table 7. The predicted values and prediction intervals for the responses of Rz, Ra and the CT are also given in Table 7. The values of Ra, Rz and the CT are expected to fall into the prediction intervals. Obtained values of confirmatory trial are seen to be within the prediction intervals. Thus, the model is verified.

After optimization, the effect on work surface behavior is also analyzed. Surface morphology is studied using the SEM- "scanning electron microscopy". SEM images correspond to optimal sample and one of the trials (trial no. 17) in design Table 4 that demonstrates worst case sample are shown in Fig. 7.

For trial 17, when current=1, T_{on}=0.55 μs, T_{off}=11.8 μs and WFR=15.5 mm/min, the values of Ra, Rz and CT are 5.815 μ, 34.637 μ, and 166.152 min, respectively. Under optimal conditions, the values of Ra, Rz and CT decreased. Especially a dramatic decrease occurred for Rz compared to trial 17.

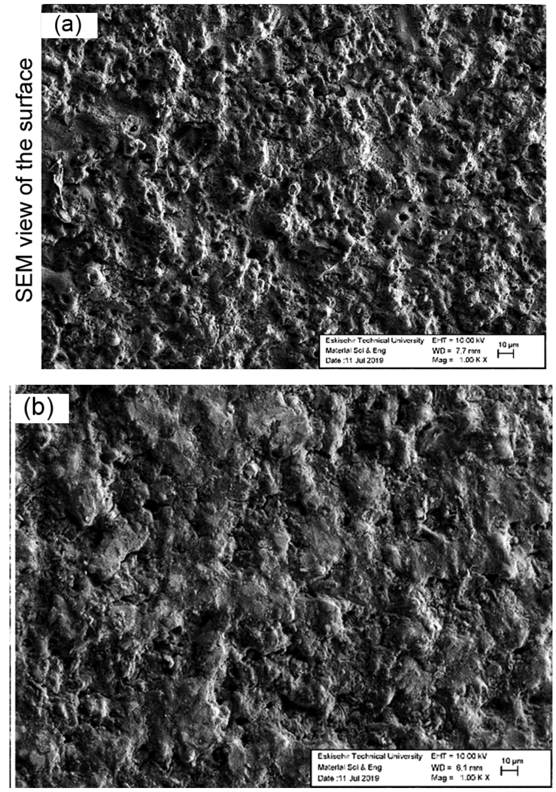

Fig. 7 — SEM view of the surface (a) optimal sample, and (b) trial no 17.

4 Conclusion

Cut 300 model machine is a new generation machine developed by seeing the shortcomings of previous wire erosion machines. In the interior equipment, servo motors, generators and capacitors have been developed. The cooling system provides a more rigid and good working environment by providing top and bottom spray cooling with both the pooled and the additional injectors. Both the material and the machine are highly cost effective due to their characteristics. Therefore, all inefficiencies that may occur when cutting the material should be eliminated by the help of RSM.

Within the scope of the study, optimization studies were conducted with the CCD experiment strategy for Ra, Rz and CT responses during the cutting of CPOH new generation cold work tool steel by wire erosion method. The CPOH steel and Cut 300 model wire erosion machine have been discussed for the first time in this study. CPOH steel is not traditional mold material. It is used frequently in precision cutting sheet metal molds to meet the increasing requirements of industry. Cut 300 machine should obtain previous wire erosion and good surface quality parts. Due to the high cost of the first investment and maintenance repair costs of the Cut 300 machine, the machine hourly rates are high. Therefore, the wire erosion machine should be operated in the most efficient way and costs should be reduced. In the study, Ra and Rz values and CT responses were optimized with CCD simultaneously. CCD facilitated the study by providing experiments systematically and in less number. The results show that the CCD strategy can be used to simultaneously optimize the SR and CT performance indicators of a high-cost machining process such as wire erosion. Analysis results showed that current, T_{on} and WFR parameters are critical for the CT, Ra and Rz surface roughness. As a result of the verification; Rz and Ra were found to be 2.23 µ and 0.38 µ respectively. In addition, CT was found to be 10.84 min. and it has been proven that the regression models can be used in prediction.

For the future work, the similar analyses can be performed for different type and quality of materials and machines, different experimental design strategies, factors and levels, and also performance indicators such as shape and dimensional measurements.

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