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RESEARCH PAPER

Machining of 304 stainless steel Using Electrochemical Machining (ECM) Process: Response Surface Methodology Approach

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ABSTRACT
In this study, Electrochemical Machining (ECM) of 304 stainless steel was applied by using Response Surface Methodology (RSM) approach for designing, analyzing, and mathematical modeling of ECM of 304 stainless steel. Electrolyte type, concentration, and current were the machining parameters. A mathematical model was provided for responses based on electrolyte types including Sodium Chloride (NaCl), Sodium Nitrate ($NaNO_3$), and Potassium Chloride (KCl). The results showed that current had the highest effect on Surface Roughness (SR) and Material Removal Rates (MRR), compared to other selected factors, and it enhanced their values up to 0.465µm and 0.425gr/min, respectively. Electrolyte concentration had the highest effect on Over Cut (OC) and increased its values. The optimum condition characterized by 0.4006gr/min MRR, 0.75mm OC, and 0.465µm SR was achieved with NaCl electrolyte, 1 molarity concentration, and 55 A current.

KEYWORDS: *Electrochemical Machining (ECM); Response Surface Methodology (RSM); Material Removal Rates (MRR); Over Cut (OC); Surface Roughness (SR).*

1. Introduction

Type 304 stainless steel has an austenitic structure and its high corrosion resistance, homogeneous structure, high ductility, and high strength make it appropriate for a wide range of applications such as energy generation equipment, food products, automobile parts, medicine, chemicals, and aerospace parts. Due to its adhesion property, this steel is attached to the tool edge, forming a make-up edge; therefore, machining this steel by means of traditional methods is quite difficult because of its adhesion property and tendency for cold work at very fast rates [1-4]. The Electrochemical Machining (ECM) process is often used for machining hard materials since the electrochemical dissolution does not depend on the hardness and toughness of the work-piece material [5-7]. Furthermore, this process enjoys some other advantages including high efficiency, high-quality surface of machined work-piece, prevention of development of residual stress in the machined work-piece, elimination of tool wear, and possibility of creating complex shapes. These features, regarded as advantages, make the process widely applicable to the aerospace, defense, molding, automotive, and medical industries [8-13].

The controlled anodic dissolution of ECM process occurs in the space between two electrodes as a result of hydrodynamic, chemical, and physical complex phenomena. They include physical movement of ions in the electrolyte solution, chemical oxidation-reduction reactions on the surfaces of electrodes, and convective motion of the electrolyte fluid within the space between two electrodes [1,8,9,11,12]. Moreover, the 304 stainless steel is composed of Nickel (Ni), Iron (Fe), and Chromium (Cr) all of which should have different dissolution voltages in ECM. These three elements have different dissolution rates under the same voltages. Due to the complex dissolution phenomenon in the space between two electrodes, statistical analysis and ECM modeling are used to obtain optimum conditions and determine the effects of involved parameters on the machining characteristics. Use of optimal parameters in the ECM process causes a significant reduction in the operator, tooling and maintenance costs, and product equipment

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with high precision. Numerous researchers have attempted to enhance the machining characteristics and determine the effective parameters through statistical analysis and mathematical modeling of the process for different materials. Asokan et al. [14] optimized the Material Removal Rates (MRR) and surface finish via Gray Relational Analysis (GRA) model and Artificial Neural Network (ANN) in machining hardened steel. The ANN model ensure better predictability based on the percentage of deviation from the training and testing data. Munda and Bhattacharyya [15] determined the optimal combination of machining parameters and their interactions based on the predominant response criteria in EN-8 work-piece machining. The proposed mathematical model was formulated to maximize MRR and minimize the value of Over Cut (OC) based on Response Surface Methodology (RSM). Ebied et al. [7] hybridized the tool frequency via low-frequency vibration to improve the accuracy of the process. Their obtained results showed that RSM was a perfect tool for analyzing the ECM process. Moreover, they found that the amplitude of the tool vibration was the most effective parameter in terms of ECM accuracy. Senthilkumara et al. [16] studied the effects of input parameters on the ECM process characteristics. In their study, RSM was used in modeling and variance analysis to determine the important levels of the machining parameters. Based on their reports, MRR was mostly affected by the applied voltage and tool feed rate rather than other parameters and the electrolyte concentration was the most important factor in Surface Roughness (SR) among other selected factors. Tang and Guo [17] investigated machining of S-03 stainless steel with the composition of $NaClO_3$ and $NaNO_3$ electrolytes. They designed orthogonal arrays to study and optimize the machining efficiency, SR, and OC. They specified the optimum conditions to obtain maximum MRR, minimum SR, and OC. Singh et al. [18] studied the effects of reaction between work-piece materials on the SR of machined work-piece. They used design orthogonal arrays in the experiments and considered the work-piece material's reaction, voltage, and inter electrode gap as input parameters and SR as a response. The work-piece material was mainly composed of mild steel, brass, and aluminum. They stated that the work-piece materials' reaction was an important factor in SR value of the machined work-piece.

Regardless of the many researches conducted so far, more researches are still required for practical applications of ECM to different types of steel. In addition, few researches have been done on 304 stainless steel machining by ECM and many studies are still required to examine the effects of input parameters on outputs and determine the values and orders of their effects. The electrolyte type, concentration, and current are the predominant parameters of the ECM process. The electrolyte type is a qualitative parameter in which different types of chloride salts and $NaNO_3$ are used as electrolytes in the ECM process and their selectivity is very important. Electrolyte concentration and current are quantitative parameters that affect the participating ions in the dissolution process and stimulate metal cations into the machining area. In order to correctly study the effects of different electrolytes, the concentration should be considered in terms of the molarity. In this study, RSM is used for designing, analyzing, and mathematical modeling of ECM of 304 stainless steel, which has not been reported yet. The electrolyte type, concentration, and current parameters are comprehensively considered as qualitative and quantitative parameters of machining, and machining characteristics of MRR, OC, and SR are the responses. In this study, for the first time, a mathematical model has been presented for these responses based on the type of NaCl, KCl impassive electrolytes, and $NaNO_3$ passive electrolyte separately. The optimal conditions for ECM are obtained with high machining efficiency, high dimensional accuracy, and appropriate surface smoothness in the machined work-pieces. These were considered as responses in this study. Analysis of Variance (ANOVA) approach was used to evaluate the adequacy of the mathematical model and determine the effects of ECM process parameters.

2. Experimental Study

2.1. Experimental set up

The ECM device, whose schematic diagram is shown in Figure 1, was designed and constructed to perform the necessary experiments. This ECM device consists of four units. The voltage of power supply is between 0 and 12 V and its maximum current is 200A. The control system includes a number of electronic circuits that can measure and control the gap changes in the machining process. This device, innovatively, uses three control methods, namely constant current density, defined feeding, and sense of work piece in specified periods. The tool feeding

unit controls the tool motion along the Z axis in the machining process. The electrolyte unit includes storing, feeding, filtering, and temperature controlling of electrolyte. There is a 5µm filter that is used to prevent impure substances from entering into the machining area to ensure a clean electrolyte in the process. In order to control the temperature of the electrolyte, a thermal exchanger system is employed. It includes a 1500w heater, a PT100 temperature sensor, a thermostat, and current relay. Machining is done in a Plexiglas's box and the work-piece is held by a particular fixture in it. Figure 2 shows the ECM device and the equipment related to performance of experiments.

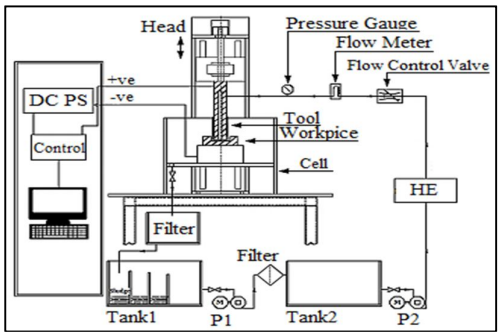

Fig. 1. Schematic diagram of ECM and its equipment

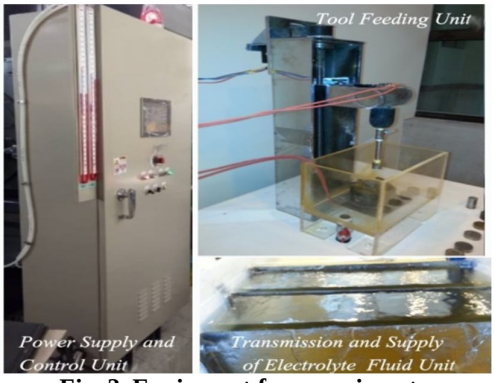

Fig. 2. Equipment for experiments

2.2 Experiment Materials

In this study, the commercial 304 stainless steel was utilized as the work-piece. The chemical composition of elements of this steel defined by quantum test and weight percentage of its alloy elements is presented in Table 1. Further, as shown in Figure 3, tools are designed and manufactured using 304 stainless steel, aluminum, and copper. The drawing of these tools is shown in Figure 4. After performing a number of experiments, due to appropriate machining characteristics of the copper tool, this tool was selected as the experimental tool. To reduce the stray current effect that leads to the reduction of unwanted dissolution, the side edges of the tool were insulated by spraying electrostatic coating of epoxy. Figures 5 and 6 show the machined samples and tools before and after coating, respectively. NaCl, $NaNO_3$, and KCl salts were used as electrolytes in the experiments. While NaCl and KCl are impassive electrolytes, $NaNO_3$ is a passive electrolyte.

Tab. 1. Weight percentage of alloying elements of 304 stainless steel

element	%Wt	element	%Wt
Al	0.024	S	0.018
C	0.046	Si	0.372
Cr	17.670	V	0.069
Cu	0.689	W	0.044
Mn	0.886	Fe	71.360
Mo	0.163	Ni	8.679

Fig. 3. Tools used in experiments

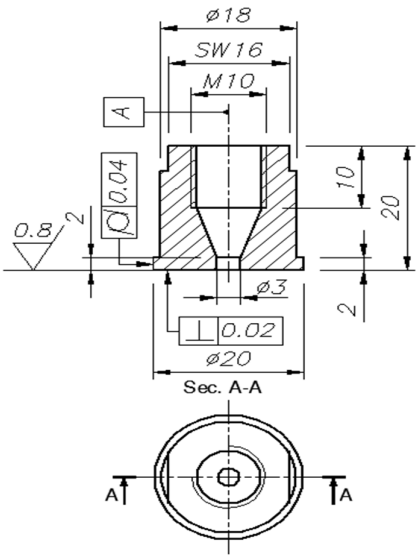

Fig. 4. Drawing of tool

The METTLER TOLEDO balance with accuracy of 0.0001gr was used to measure the value of MRR in examinations. The experimented samples were washed with distilled water and completely dried; then, they were weighted before and after the experiments. The MRR was calculated using Eq. (1).

$$MRR = \frac{M_1 - M_2}{t} \quad (1)$$

where MRR is the MRR value (gr/min), M_1 is the mass of the work-piece before machining (gr), M_2 is the mass of the work-piece after machining (gr), and t is machining time (min).

The profile projector measuring device, Starret HS1000, was used to measure the created OC in the experimented samples. In this device, first, the magnified image of the machined samples was created on the screen device and then, several points were introduced on their side edges and the average of machined diameter was calculated. The value of OC was calculated by Eq. (2):

$$OC = \frac{Dp - Dt}{2} \quad (2)$$

where D_p is the machined work-piece diameter (mm) and D_t is the tool diameter (mm).

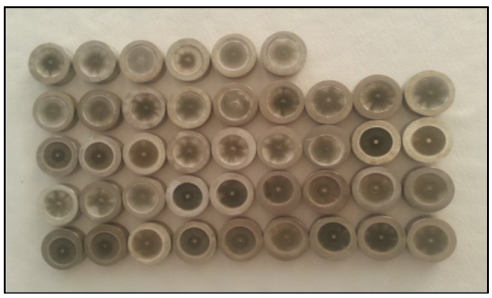

Fig. 5. Machined work pieces in experiments

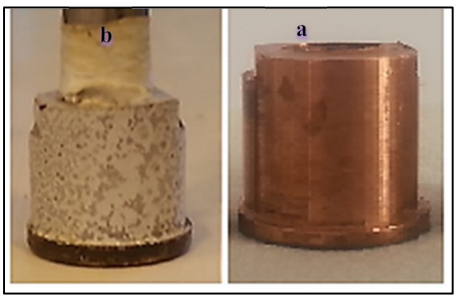

Fig. 6. (a) Copper tool before coating and (b) Copper tool after coating

The roughness tester device, Mahr Perthometer, was employed to measure the SR of samples. The Roughness average (Ra) was measured at the central, middle, and lateral points of the work-piece surface and their average value was considered the SR of the machined work-pieces.

2.2.1. Design of experiments

The design of experiments used in this study was RSM. The process variables were electrolyte type, concentration, and current. As shown in Table 2, these variables are presented at three levels, at which 38 experiments were performed. NaCl, $NaNO_3$, and KCl electrolytes were taken into consideration in the design of experiments as qualitative parameters with varying concentration degrees of 1, 1.5, and 2 molarity, respectively. Molarity is the mole number of a dissolved substance in one liter of solution, as calculated by Eq. (3). The characteristics of the used electrolytes in the experiments are given in Table 3. Other process parameters including the applied voltage (10V), electrolyte flow rate (3L/min), background pressure of electrolyte (0.05 MP), electrolyte temperature (26 ± 1ºC), initial setting gap (0.3 mm), and machining time (5min) were kept constant during the experiments.

$$\text{Molarity(M)} = \frac{\text{the mole number of a dissolved substance}}{\text{one liter of solution}} \quad (3)$$

3. Results and Discussion

3.1. Response surface methodology

Response Surface Methodology (RSM) is an empirical modeling method for determining the relationship between different process parameters and responses with different criteria and exploring the importance of the process input parameters w.r.t the surface of responses. Compared to the full factorial method, in the proposed method, the number of experiments was reduced so that the required cost and time for experiments could be consequently decreased. RSM is widely used for examining the effects of individual parameters and their interactions [16, 20-24]. The experimental design and the obtained results for each response are presented in Table 4. In this study, the design of experiments was performed based on the response surface methodology using Design Expert software. Given that 3 levels were assigned to each of input parameters including the electrolyte type, concentration, and current, 38 experiments were conducted and MRR, OC, and SR were considered as responses. The results of the experiments are presented in Table 4.

To obtain the mathematical models of responses, ANOVA was performed using Design Experiment software; F-value and adjusted R2 parameters were used as criteria to select the highest polynomial order. The information flowchart is shown in Figure 7.

Tab. 2. Process parameters and their levels

	Levels		
Process parameters	Low	Medium	High
Electrolyte concentration (A)	1	1.5	2
Current (B)	35	45	55
Electrolyte type (C)	NaCl	$NaNO_3$	KCl

Tab. 3. Characteristics of the electrolytes [19]

Electrolyte	Chemical formula	Group type	Structural formula	Molar mass (gr/M)	The limiting Molar conductivity cm^2/Ω	Ionic mobility U in 20°C $cm^2/v.s$	Solubility in water 25°C (gr/lit)	Density (20°C) gr/cm^3
Sodium chloride	NaCl	salt	Na _ Cl	58.44	126.45	$U_{Cl^-}=7.91\times10^{-4}$ $U_{Na^+}=5.19\times10^{-4}$	359	2.17
Sodium nitrate	$NaNO_3$	Salt		84.98	121.56	$U_{NO3^-}=7.4\times10^{-4}$ $U_{Na^+}=5.19\times10^{-4}$	912	2.257
potassium chloride	KCl	salt	K _ Cl	74.54	149.85	$U_{Cl^-}=7.91\times10^{-4}$ $U_{K^+}=6.1\times10^{-4}$	359	1.984

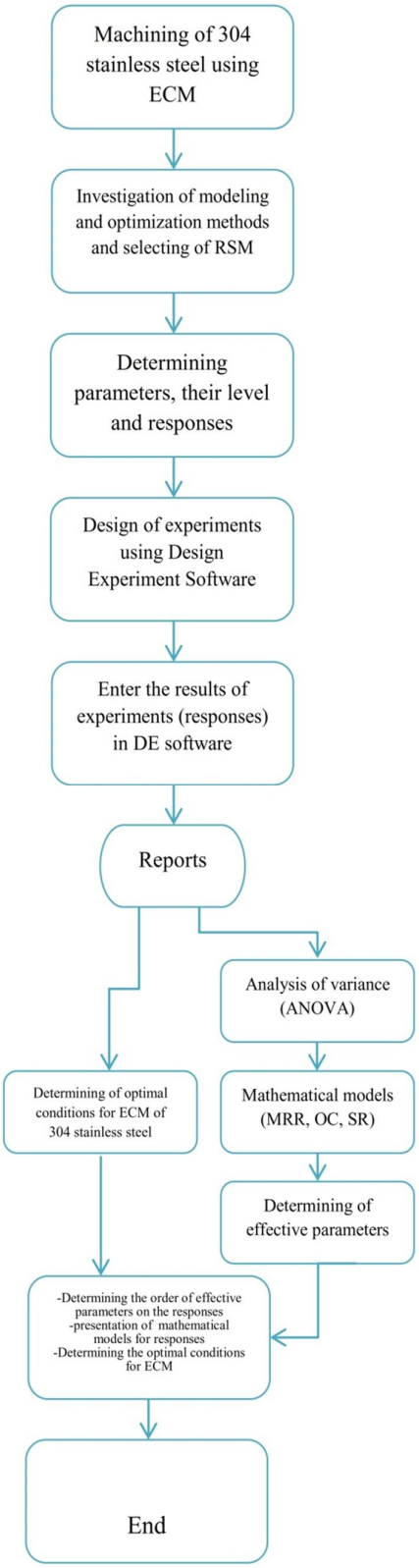

Fig. 7. Flowchart of information

3.1.1. Mathematical model for material removal rate (MRR)

The results of various polynomial orders showed that 2FI versus linear model had a P-value less than 0.05 and adjusted R^2 higher than other available models. These results suggested that the 2FI versus linear model would provide the best response surface for modeling the output

parameters of MRR. Table 5 represents the details of ANOVA used for 2FI versus linear model for MRR. The F-value and p-value for each of the process parameters and their interactions are presented in Table 4. According to the results, the most significant parameter of MRR with the lowest p-value and highest F-value was current. Other significant factors were electrolyte type, concentration, and interaction between electrolyte concentration and electrolyte type, respectively. These analyses were repeated by omitting the terms with a p-value higher than 0.05; the resulting mathematical models are presented in Eqs. (4) to (6).

Electrolyte type: NaCl (4)

$$MRR = + 1.40767 + 0.013708A + 2.4564\times10^{-3}B - 1.28329\times 10^{-4} AB$$

Electrolyte type: $NaNO_3$ (5)

$$MRR= +1.35613 + 0.018809A + 2.64899 \times 10^{-3} B - 1.283329 \times 10^{-4} AB$$

Electrolyte type: KCl (6)

$$MRR = +1.41838 + 0.012510A + 2.32969 \times 10^{-3} B - 1.28329\ 10^{-4} AB$$

where A is electrolyte concentration and B is current.

3.1.2. Mathematical model for over cut (OC)

According to the results obtained from ANOVA analysis, the Linear versus Mean model had the lowest P-value and the highest adjusted-R^2 among other polynomial orders and provided the best fit for the response surface of OC. Details of the ANOVA analysis for the Linear versus Mean model of OC are given in Table 6. Accordingly, the electrolyte concentration had the lowest p-value and the highest F-value among other input parameters. The mathematical model of OC is presented in terms of the electrolyte type in Eqs. (7) to (9).

Electrolyte type: NaCl (7)

$$OC = +1.07123 + 0.38126A – 0.012759B$$

Electrolyte type: $NaNO_3$ (8)

$$OC = +0.72904 +0.38126A - 0.012759B$$

Electrolyte type: KCl (9)

$$OC = +1.24860 + 0.38126A – 0.012759B$$

where A is electrolyte concentration and B is current.

Tab. 4. Design of experiments and results for responses

Run	Factor 1 A:Electrolyte concentration Mol/Lit Of Water	Factor 2 B:Current A	Factor 3 C:Electrolyte type	Response 1 MRR gr/min	Response 2 OC mm	Response 3 SR (Ra), μm
1	1.50	45.00	$NaNo_3$	0.2309	0.443	1.007
2	1.00	55.00	$NaNo_3$	0.2767	0.181	0.777
3	1.50	55.00	$NaNo_3$	0.316	1.147	0.354
4	2.00	35.00	NaCl	0.2915	1.367	1.908
5	1.50	45.00	NaCl	0.3399	1.076	1.099
6	1.50	45.00	$NaNo_3$	0.235	1.508	0.447
7	1.50	45.00	KCl	0.3469	1.316	1.321
8	2.00	55.00	KCl	0.4267	1.253	1.163
9	1.00	35.00	$NaNo_3$	0.1627	0.697	0.583
10	1.00	45.00	KCl	0.3475	1.086	0.944
11	1.00	55.00	KCl	0.4157	0.801	0.898
12	1.00	35.00	KCl	0.2651	1.061	1.661
13	1.50	35.00	KCl	0.2831	1.584	1.922
14	1.50	35.00	NaCl	0.2745	1.146	1.706
15	2.00	45.00	$NaNo_3$	0.2534	0.65	1.298
16	2.00	55.00	$NaNo_3$	0.337	0.539	1.372
17	2.00	55.00	NaCl	0.4174	1.097	0.844
18	2.00	55.00	KCl	0.41674	1.21	1.26
19	1.00	45.00	NaCl	0.3273	0.871	1.02
20	2.00	45.00	NaCl	0.3527	1.214	1.698
21	2.00	35.00	KCl	0.3131	1.736	1.96
22	2.00	35.00	$NaNo_3$	0.182	0.776	1.253
23	1.00	45.00	$NaNo_3$	0.20916	0.262	0.716
24	2.00	55.00	NaCl	0.4174	0.708	0.743
25	1.00	45.00	KCl	0.3375	0.943	1.086

26	1.50	55.00	KCl	0.4209	1.024	0.927
27	1.50	55.00	NaCl	0.4168	0.85	0.459
28	2.00	55.00	$NaNo_3$	0.3295	1.303	0.54
29	1.00	45.00	NaCl	0.3173	1.02	0.874
30	1.50	55.00	$NaNo_3$	0.314	0.352	1.143
31	1.00	45.00	$NaNo_3$	0.20916	0.72	0.26
32	1.00	35.00	$NaNo_3$	0.1436	0.332	0.652
33	2.00	45.00	KCl	0.3554	1.568	1.742
34	1.00	55.00	NaCl	0.4107	1.298	0.65
35	1.00	35.00	NaCl	0.2591	0.984	1.374
36	2.00	35.00	$NaNo_3$	0.1767	1.672	0.779
37	1.50	35.00	$NaNo_3$	0.1554	0.583	0.834
38	2.00	45.00	$NaNo_3$	0.2481	0.654	1.328

Tab. 5. ANOVA for 2FI versus Line of MRR

Source	Sum of Squares	Degrees	ofMean Square	F -Value	p-Value
Model	0.028	9	3.077E-003	392.46	*< 0.0001*
A-Electrolyte	*6.159E-004*	*1*	*6.159E-004*	*78.56*	*< 0.0001*
B-Current	*0.012*	*1*	*0.012*	*1585.88*	*< 0.0001*
C-Electrolyte Type	*0.012*	*2*	*6.207E-003*	*791.71*	*< 0.0001*
AB	*6.628E-006*	*1*	*6.628E-006*	*0.85*	*0.3657*
AC	*5.254E-005*	*2*	*2.627E-005*	*3.35*	*0.0496*
BC	*4.296E-005*	*2*	*2.148E-005*	*2.74*	*0.0819*
Residual	2.195E-004	28	7.840E-006		
Lack of Fit	*1.752E-004*	*17*	*1.030E-005*	*2.55*	*0.0588*
Pure Error	*4.436E-005*	*11*	*4.033E-006*		
Cor Total	0.028	37			

Tab. 6. ANOVA for Linear versus Mean of OC

Source	Sum of Squares	Degrees	ofMean Square	F -Value	p-Value
Model	2.93	4	0.73	8.04	0.0001
A-Electrolyte	*0.97*	*1*	*0.97*	*10.59*	*0.0026*
B-Current	*0.38*	*1*	*0.38*	*4.20*	*0.0486*
C-Electrolyte Type	*1.88*	*2*	*0.94*	*10.34*	*0.0003*
Residual	3.01	33	0.091		
Lack of Fit	*1.16*	*22*	*0.053*	*0.31*	*0.9899*
Pure Error	*1.85*	*11*	*0.17*		
Cor Total	5.94	37			

3.1.3. Mathematical model for surface roughness (SR)

According to the results of the ANOVA analysis, the 2FI versus Liner model had the lowest P-value and the highest adjusted-R^2 among other polynomial orders and provided the best fit for the response surface of SR. Details of ANOVA analysis for the 2FI versus Liner model of SR are presented in Table 7. Accordingly, the most significant parameter influencing the SR of work-piece was current, which had the lowest p-value and the highest F-value among other input parameters. Other important parameters included electrolyte concentration, electrolyte type, and interaction between current and electrolyte type, respectively.

The mathematical model of SR is presented in terms of electrolyte type in Eqs. (10) to (12).

Electrolyte type: NaCl (10)

$SR= +2.27597 +0.83396 A – 0.039762B – 8.31614\times 10^{-3} AB$

Electrolyte type: $NaNO_3$ (11)

$SR= -0.43051 +0.87088 A +0.011257 B - 8.31614\times 10^{-3} AB$

Electrolyte type: KCl (12)

$SR = +1.94863 +0.87208 A -0.028909 B - 8.31614\times 10^{-3} AB$

where A is electrolyte concentration and B is current.

4. Conclusions

In this study, the operation of ECM process with respect to the machining characteristics of 304 AISI stainless steel including material removal rates, surface smoothness, and over cut was evaluated. The present study employed the RSM design to investigate the effects of different parameters on the MRR, surface smoothness, and OC and developed an empirical model for each response based on machining of parameters. Further, the optimum conditions were reported for machining this steel. The results of this study are summarized as follows:

Tab. 7. ANOVA for 2FI versus Line of SR

Source	Sum of Squares	Degrees of Freedom	Mean Square	F -Value	p-Value
Mode	6.10	9	0.68	11.94	< 0.0001
A-Electrolyte concentration	*1.56*	*1*	*1.56*	*27.42*	*< 0.0001*
B-Current	*1.85*	*1*	*1.85*	*32.51*	*< 0.0001*
C-Electrolyte Type	*2.12*	*2*	*1.06*	*18.69*	*< 0.0001*
AB	*0.028*	*1*	*0.028*	*0.49*	*0.4896*
AC	*1.928E-003*	*2*	*9.642E-004*	*0.017*	*0.9832*
BC	*1.23*	*2*	*0.62*	*10.84*	*0.0003*
Residual	1.59	28	0.057		
Lack of Fit	*0.53*	*17*	*0.031*	*0.32*	*0.9828*
Pure Error	*1.06*	*11*	*0.097*		
Cor Total	7.69	37			

1- Among the studied machining parameters, current had the highest effect on MRR and SR. MRR increased by increasing the current and the surface smoothness of work-piece improved to 0.65 µm. In addition, electrolyte concentration had the greatest effect on OC and caused a decrease in the machining accuracy and increased OC to 1.568mm.
2- The least value of OC was obtained for $NaNO_3$ (0.18 mm), NaCl (0.7mm), and KCl (0.8 mm) electrolytes, respectively.
3- The optimal conditions for the 304 stainless steel machining by the ECM process were characterized by MRR 0.4006gr/min, OC 0.7507mm, and SR 0.465µm in the NaCl with a molar concentration of 1 molarity and current of 55A.

5. Acknowledgements

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