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Multi-objective optimization of electrochemical finishing for attaining the required surface finish and geometric accuracy in the hole-making process

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Abstract. Obtaining the required surface finish and geometric accuracy, together with attaining a high production rate, is a challenge in finishing the inner surfaces of steel pipes and bushes. One of the promising techniques for the reduction of the surface roughness of metal parts is electrochemical machining. In this paper, the roughness and dimensional inaccuracy of the internal surface of a CK45 steel bush were controlled electrochemically. For this, a novel electrochemical finishing setup was constructed. The effect of electric potential difference along with temperature, flow rate, and concentration of electrolyte on the process outputs, including the material removal rate, surface roughness, and dimensional accuracy, were investigated. The Box-Behnken Design was utilized to design the empirical experiments. Analysis of variance was performed to validate the experimental models. Also, multi-objective optimization was implemented using response surface methodology to achieve a predetermined level of surface roughness and dimensional accuracy, along with maximizing the material removal rate.

1. Introduction

Electrochemical Machining (ECM) is an unconventional manufacturing process that is based on the localized anodic dissolution of the metal workpiece by applying an electric voltage between the tool and the workpiece. ECM can be regarded as a finishing process and may be employed for the enhancement of surface finish on the workpiece material [1,2]. Electrochemical finishing is a noncontact process in which the workpiece does not come into contact with the cathode tool, and consequently, the tool wear is negligible. Due to this advantage, electrochemical finishing stands as an important candidate for polishing the intricate metallic parts and the internal surfaces of metallic bushes and tubes. Referring to a review paper by Kumar and Pabla [3], several variables like electrolyte conditions, tool (cathode) and workpiece material, machining ge-

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ometry, and electrolyte flow rate and flow pattern affect the performance of the ECM process.

A large and growing body of literature has investigated the influence of electrochemical finishing process variables on the final surface roughness of intricate metallic articles and metallic tubes. For example, Zhang et al. [2] investigated the effect of electrolyte composition on the surface roughness and Material Removal Rate (MRR) of Hastelloy X superalloys. Zaho et al. [4] increased the surface smoothness of slotted tube coronary stents electrochemically. The workpiece was made of 316L stainless steel. The input variables in their experimental study were the electric potential difference, Inter-Electrode Gap (IEG), the temperature of the electrolyte, and electrolyte flow rate. They found that the resulting surface roughness was strongly influenced by electrolyte flow and electric overvoltage. Lee [5] investigated the electrochemical finishing of stainless steel tubes and analyzed the effect of current density, machining duration, temperature of electrolyte, and IEG on the surface smoothness of stainless steel tubes. The best results were obtained for his case at a temperature close to 68°C and when the IEG was 1.0 mm. Gallegos et al. [6] evaluated the effect of process variables in ECM of stainless steel 316 on the resulting surface finish on steel tube samples. The input machining parameters were IEG, electric potential, and temperature and flow rate of the electrolyte. They evaluated the impact of each input parameter on the surface quality of machining. They found that the overvoltage and electrolyte flow rate have a substantial effect on the final surface roughness of the workpiece. Also, the electrolyte temperature and IEG had a negligible influence on the resulting surface finish of the workpiece.

Hocheng and Pa [7] employed electrochemical polishing to improve the surface finish of the inner holes in tool steel workpieces. They applied continuous, direct current between the anode and the cathode. The size of the electrode and the concentration and chemical composition of the electrolyte were the input factors in the experiments. They showed that a lower current density along a lower electrode feed rate results in a better surface finish on the workpiece. Also, they found the optimum polishing condition. Lou et al. [8] investigated the ECM finishing characteristics of a workpiece with corner features. They evaluated the distribution of current density on the workpiece. They analyzed the effects of the shape of corners, the IEG, the production of bubbles, and electrolyte flow. They concluded that the relative reduction of the current density at the inner corner area is the reason for the insufficient surface quality at the corner area. Mahdavinejad and Hatami [9] employed the electrochemical polishing process on a gun pipe. They investigated the impact of polishing time and the temperature of the electrolyte on the surface roughness of the workpiece. Also, they obtained the optimized polishing parameters. Wang et al. [10] investigated the impact of the electrolyte flow field on the stability of machining and the occurrence of surface defects on complex structures like aero-engine blades. They introduced the tangential flow field as a new flow field by which the surface of the machined blades had a very low roughness without short circuit burns and flow marks. Wang et al. [11] studied the effect of the electrolyte flow field on the consistency of machining allowance for blisk channels. They showed that the conventional flow modes with a constant flow rate of the electrolyte cannot maintain the consistency of allowance after the finishing of complicated channels. However, with the variable feed rate mode, the consistency of the allowance distribution is improved, and the machining accuracy is increased. Chaghazardi et al. [12] investigated the electrochemical polishing of the internal walls in stainless steel 316 tubes. They focused on the effect of parameters such as IEG and the size of the tubing on the final roughness and brightness of the workpiece. They concluded that under a proper selection of input parameters like electric voltage, polishing time, and electrolyte hydrodynamic conditions, the brightness increased, and surface roughness decreased. Lee et al. [13] reduced the surface roughness of additively manufactured 17-4 PH stainless steel electrochemically by using a mixture of phosphoric and perchloric acids. They commented that the electropolishing process increased the surface hardness and corrosion resistance of the workpiece. Chaghazardi and Wüthrich [14] explained the necessity of employing the design of experiments to find the optimum levels of process factors in complicated finishing processes like electrochemical polishing.

Although the electrochemical finishing can be applied to enhance the surface finish on the internal holes and features of metallic parts, dimensional accuracy is affected simultaneously. However, far too little attention has been paid to evaluating and controlling the dimensional accuracy of the finished part. This is while the electrochemical finishing processes have a high potential for simultaneously controlling both surface roughness and dimensional inaccuracies on the internal holes and features of metallic parts. Multi-objective optimization is the suggested approach for such a condition where the system needs to be optimized for multiple conflicting objectives [15].

This paper will examine the possibility of controlling both surface roughness and dimensional inaccuracy (run-out error) on the inner holes of carbon steel bushes, which are subjected to the electrochemical finishing operation. For this, the empirical evaluation of the impact of process parameters on dimensional accuracy and surface finish of the polished surfaces is performed systematically. A novel electrochemical finishing setup was designed and constructed to improve the surface roughness and dimensional accuracy on the inner surfaces of CK45 steel bushes. The experiments are designed using the Box-Behnken Design (BBD) method in Response Surface Methodology (RSM), and an empirical formula that relates the input process parameters with dimensional accuracy and the surface finish of the final polished surface is derived. The input process parameters are temperature, concentration, and flow rate of electrolyte along the electric potential. The adequacy of the model is evaluated by Analysis of Variance (ANOVA). Finally, by using multi-objective optimization, the necessary conditions for attaining the required surface roughness and maximum finishing rate, along with keeping the accuracy above a predetermined value, are obtained.

2. Materials and procedures

For electrochemical finishing of the inner surface of metal pipes, a particular ECM setup was built. The setup involves a DC electric power unit, a tool feeding system that supplies both linear and rotational movement for the tool, an electrolyte feeding unit, and a fixture for holding the workpiece. Within the process, the gap between the workpiece and the tool or IEG (inter-electrode gap) almost remains unchanged. Figure 1 shows the electrochemical finishing setup constructed for finishing the inner surfaces of CK45 steel pipes.

In this research, NaCl solution was selected as the electrolyte. This electrolyte has high current efficiency and low price [16]. The concentration of NaCl solution was one of the input variables. The second input variable was the temperature of the electrolyte, which is controlled via a thermostat with 1°C accuracy. The electrolyte flow rate, as the third input variable, was adjusted by an electric pump, and the electric potential, as the last process variable, was adjusted by an electric rectifier. The electro-finishing tool was a round disc with an outer diameter of 19.5 mm and thickness of 10 mm, which was fixed on a shaft. The tool material was copper 99%. During the finishing process, the tool moved across the workpiece, and the moving speed was controlled by a stepper motor. The workpiece was grasped by the upper and lower fixtures. The electrolyte passes through the upper fixture and IEG and then gets out of the lower fixture. By employing the electric potential between the anode workpiece and the cathode copper tool, the inner surface of the workpiece dissolves electrochemically. Figure 2 shows the cross-section of the upper and lower fixtures and the workpiece along the copper tool.

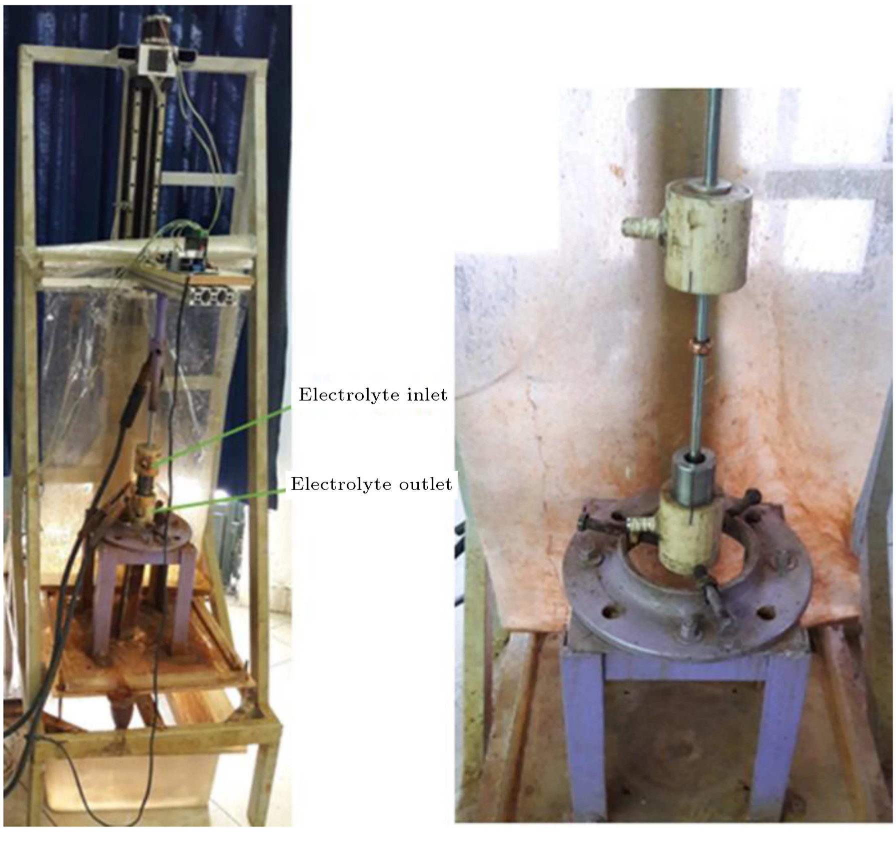


Figure 1. Electro polishing setup and workpiece fixture.

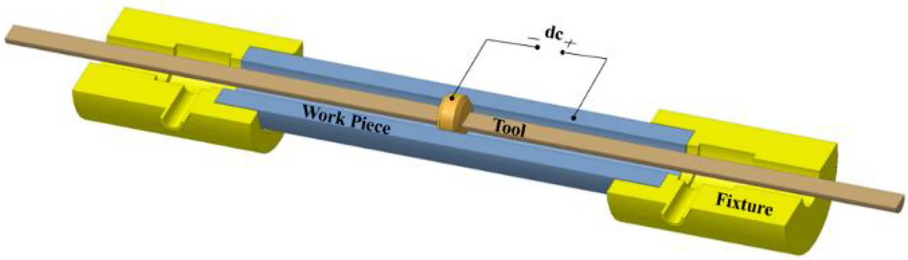


Figure 2. The tooling system for the electro finishing.

3. Experimental design method

In this research, the process response variables are surface roughness (Ra), MRR, and dimensional accuracy. MRR was calculated using Eq. (1) [17]:

$$MRR = \frac{(IW) - (FW)}{T}, \tag{1}$$

where IW and FW are the Initial and Final Weight of the workpiece measured via a precise digital weight meter with the resolution of 0.001 gram, and T is the machining time. The average roughness (Ra) of the finished face was determined by a Mitutoyo roughness tester with the resolution of 0.01 μm. To evaluate the dimensional accuracy, the deviation of end-to-end diameters of the inner hole in the workpiece was measured.

The design of experiments was conducted using the BBD method, which is adopted with RSM. By using the RSM, a functional relationship between a response variable, y, and some input variables denoted by $x_1, x_2, ..., x_k$ is obtained. Generally, this functional relationship is approximated via a low-degree polynomial function [18]. For example, the general second-order polynomial function may be represented by Eq. (2):

$$y = c_0 + \sum_{i=1}^{n} c_i x_i + \sum_{i=1}^{n} c_{ii} x_i^2 + \sum_{i,j=1; j \prec i}^{n} c_{ij} x_i x_j, \tag{2}$$

here, y is the response parameter, and c_i and c_{ij} are the first- and second-order regression coefficients, respectively. The RSM method enables one to analyze the influence of each input parameter and their interactions on the response. Also, the empirical mathematical model is obtained relating input variable to output parameters using RSM. This model is used for the optimization of electrochemical finishing conditions.

3.1. BBD in RSM

Experimental designs that utilize second-degree models are known as second-order designs. The BBD is one of the most commonly used second-order designs. Box-Behnken is a spherical design in which all the test points lie on a sphere. In this design method, the test points do not coincide with the vertices of the cubic region created by the upper and lower limits of each variable [18]. The number of experiments (N) in BBD is obtained by $N = k^2 + k + c_p$, where k is the number of input factors and c_p is the number of repeated tests as the central point. The test points in the BBD lay on the central point and the middle points of the edges of a cube [19].

Table 1. Factors and levels used in the Box-Behnken Design (BBD).

Factors	**Levels**		
Voltage (V)	6	9	12
Flow rate (l/min)	20	42.5	65
Concentrations (g/l)	25	50	75
Temperature (°C)	30	45	60

The BBD method in the RSM was employed via design expert software. Table 1 represents the actual values of the input variables. The selected range for the input variables is based on previous literature [20]. Other influential process variables like initial IEG, tool longitudinal movement speed (feed), and machining time were constant during the finishing process with the values of 0.4 mm, 15 mm/s, and 20 minutes, respectively.

The experiments suggested in the BBD for the input variables (voltage, flow rate, electrolyte concentration and temperature) are described in the Table 2. The number of the suggested experimental runs is 27, and for each experiment, the average surface roughness (Ra), MRR, and geometric tolerance were measured.

3.2. Analysis of Variance (ANOVA)

To evaluate the model adequacy, an ANOVA was performed. By this analysis, some statistical quantities like the sequential P-value, lack of fit P-value, deterministic coefficient R^2, and adjusted R^2 are calculated to evaluate the model's precision and adequacy. For an acceptable model, the sequential P-value should be less than 0.05, and the P-value of lack of fit should be more than 0.05. Also, the difference between deterministic coefficient R^2 and adjusted R^2 should be smaller than 0.2, and the amount of precision adequacy should be more than 4 [20].

Table 2. The designed experiments.

Std	Run	Factor A: Voltage (V)	Factor B: Flow rate (l/min)	Factor C: Concentration (g/l)	Factor D: Temperature (°C)	Response1 *Ra*	Response MRR (g/min)	Response Tolerance (mm)
17	1	6	42.5	25	45	2.5	0.275	0.05
11	2	6	42.5	50	60	2.55	0.345	0.03
5	3	9	42.5	25	30	2.43	0.495	0.02
2	4	12	20	50	45	2.39	0.94	0.01
1	5	6	20	50	45	2.6	0.305	0.02
6	6	9	42.5	75	30	2.57	0.73	0.05
16	7	9	65	75	45	2.53	0.875	0.06
20	8	12	42.5	75	45	2.45	1	0.02
14	9	9	65	25	45	2.4	0.56	0.03
23	10	9	20	50	60	2.6	0.825	0.01
19	11	6	42.5	75	45	0.7	0.4	0.05
13	12	9	20	25	45	2.52	0.545	0.01
25	13	9	42.5	50	45	2.53	0.765	0.03
7	14	9	42.5	25	60	2.35	0.58	0.01
24	15	9	65	50	60	2.45	0.82	0.05
4	16	12	65	50	45	2.28	0.94	0.02
18	17	12	42.5	25	45	2.25	0.71	0.01
15	18	9	20	75	45	2.75	0.88	0.05
22	19	9	65	50	30	2.47	0.645	0.04
26	20	9	42.5	50	45	2.5	0.78	0.02
3	21	6	65	50	45	2.48	0.415	0.02
9	22	6	42.5	50	30	2.58	0.3	0.02
12	23	12	42.5	50	60	2.35	0.99	0.01
8	24	9	42.5	75	60	2.54	0.83	0.02
21	25	9	20	50	30	2.65	0.64	0.01
10	26	12	42.5	50	30	2.4	0.84	0.01
27	27	9	42.5	50	45	2.51	0.75	0.03

3.3. Optimization methodology

After extracting the functional relationships among the input variables and response outputs, the multi-objective optimization was implemented by combining the responses into a single-purpose function, known as the desirability function. The desirability $D(y)$ is usually a (weighted) mean of "n" distinct desirability functions, $d_i(y_i)$, one for each response variable, y_i. Each $d_i(y_i)$ value is converted from the related response y_i and scaled to be between 0 and 1. The value of zero for the desirability function indicates an unacceptable response level, and one indicates that the optimal level of related response is achieved. Eq. (3) represents the desirability function $D(y)$:

$$D(y)=(d_1(y_1)^{k_1}\times d_2(y_2)^{k_2}\times\ldots\times d_n(y_n)^{k_n})^{\frac{1}{\sum_i k_i}}, \quad (3)$$

where y_i is the measured value of response i, $d_i(y_i)$ is the transformed desirability value of i'th response, and k_i represents the relative significance of response i compared to others [21].

In our problem, we assumed that all the outputs have the same significance; thus, $D(y)$ turns out to be a geometric mean of all "n" converted responses without any weights. Consequently, to optimize the responses simultaneously, we were looking for the values of input variables (x_i) that maximize $D(y)$. This was performed using design expert software, which makes the numerical optimization of desirability function by hill climbing technique [20].

4. Results of the experimental study

4.1. Empirical model for surface roughness

To measure the average roughness of the finished surface, the steel bush was cut into two pieces, and the roughness was recorded by a Mitutoyo surface roughness tester. Experimental results were fed to RSM, and the regression coefficients that relate the surface roughness to the input factors were extracted and indicated in Table 3.

In Table 3, A, B, C, and D are the electric potential, electrolyte flow rate, concentration, and temperature, respectively. As demonstrated in Table 3, the P-value of the first three input factors is less than 0.05. Accordingly, these factors are the main influential factors on surface roughness, and the roughness has a linear relationship with its influential input factors. Increasing the electric voltage and electrolyte flow rate leads to the generation of a smoother surface. Additionally, an increase in electrolyte concentration results in an increase in surface roughness. These effects have been shown by 3D response surfaces, which are indicated by Figure 3 (parts a and b).

To evaluate the efficiency of the obtained model, ANOVA was performed. The outcomes are represented in Table 4. Based on ANOVA, the linear model had a P-value of less than 0.05 with a high value for precision adequacy. Thus, this model was suggested by the Design Expert software.

4.2. An empirical model for MRR

For measuring MRR, the weight difference of the workpiece before and after the finishing was determined by a precise digital mass scale with a resolution of 0.001 gr. Then, the MRR was calculated by Eq. (2). After performing the predetermined experiments and feeding the results to the Design Expert, the regression coefficients that relate the MRR to the input factors were extracted and indicated in Table 5.

The input factors and their cross products with P-values smaller than 0.05 were the suggestive parameters that affect the MRR. Accordingly, the main effective parameters were electric voltage and electrolyte concentration. Electric voltage had a nonlinear (second-order) influence on the MRR. Other factors had a negligible influence on the MRR. 3D plots of MRR as

Table 3. The empirical model of surface roughness.

Relationship		Factor	Coefficient	P-value
Intercept			2.5	—
Main effects	Linear	A	–0.1117	< 0.0001
	Linear	B	–0.0750	< 0.0001
	Linear	C	0.0950	< 0.0001
	Linear	D	–0.0217	0.1398

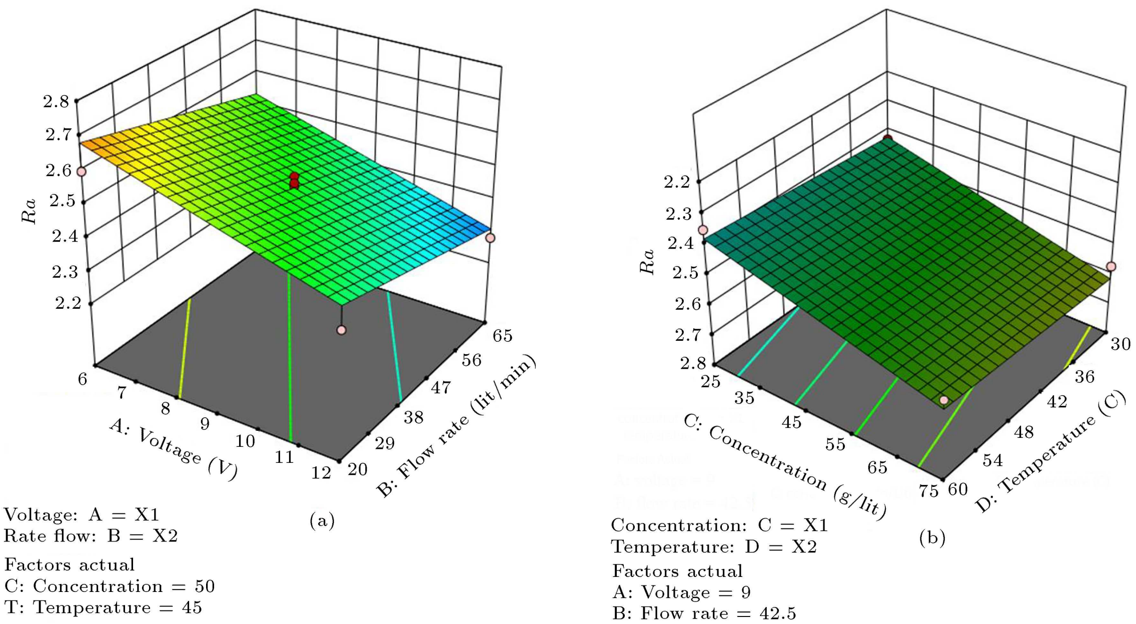


Figure 3. (a) Evaluation of surface roughness against voltage and flow rate; and (b) electrolyte concentration and temperature.

Table 4. Results of Analysis of Variance (ANOVA) for surface roughness.

Source	Sequential P-value	Lack of fit P-value	Adjusted R^2	Predicted R^2	Precision adeq	
Linear	< 0.0001	0.0850	0.8374	0.7849	19.6061	Suggested
2FI	0.9629	0.0652	0.7938	0.5833	—	
Quadratic	0.0939	0.0855	0.8514	0.6091	—	
Cubic	0.9657	0.0256	0.6918	–5.6550	—	Aliased

Table 5. The regression coefficients of input factors for the surface roughness.

Relationship		Factor	Coefficient	P-value
Intercept			0.7650	—
Main effects	Linear	A	0.2817	< 0.0001
	Linear	B	0.0100	0.3929
	Linear	C	0.1292	< 0.0001
	Linear	D	0.0617	0.0001
Interaction	Quadratic	A^2	–0.1119	< 0.0001
		B^2	0.0044	0.8004
		C^2	–0.0594	0.0043
		D^2	–0.0394	0.0383
	Cross production	AB	–0.0275	0.1848
		AC	0.0413	0.0565
		AD	0.0262	0.2041
		BC	–0.0500	0.8024
		BD	–0.0025	0.9003
		CD	0.0037	0.8511

Table 6. Results of ANOVA for Material Removal Rate (MRR).

Source	Sequential P-value	Lack of fit P-value	Adjusted R^2	Predicted R^2	Precision adeq	
Linear	< 0/0001	0.0384	0.8963	0.8714	—	
2FI	0.9101	0.0303	0.8733	0.7830	—	
Quadratic	0.0002	0.9698	0.8984	0.9208	28.2002	Suggested
Cubic	0.0346	0.9943	0.8039	0.9225	—	Aliased

a function of input factors were made based on the extracted empirical model and represented in Figure 4(a) and (b).

As shown in Figure 4, voltage has the most substantial effect on MRR, and increasing potential differences have led to a rapid increase in MRR. Also, an increased electrolyte concentration and temperature led to the increment in MRR. Electrolyte flow rate has the weakest effect on MRR. The results of ANOVA are shown in Table 6. As represented in Table 6, a quadratic model could simulate the dependence of MRR on the input variables. This model had the smallest P-value and the most considerable precision.

4.3. An empirical model for accuracy

During the electrochemical finishing, the diameter of the inner hole of the workpiece changes. Similar to other hole-forming and finishing processes, the diameter of the two ends of the hole may differ, and a type of dimensional inaccuracy may occur on the workpiece. This geometrical inaccuracy was defined as a geometric tolerance for the hole-finishing process and should be

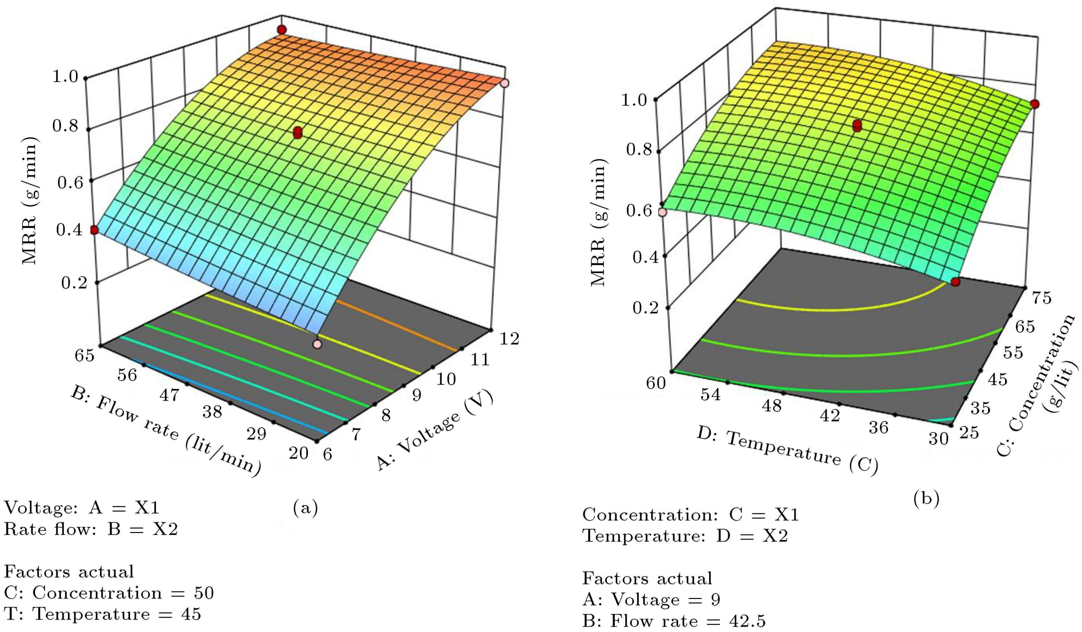


Figure 4. (a) Evaluation of Material Removal Rate (MRR) as a function of voltage and flow rate; and (b) effect of electrolyte concentration and temperature on MRR.

Table 7. The extracted regression coefficients for the tolerance of the operation.

Relationship		Factor	Coefficient	P-value
Intercept			0.0263	—
Main effects	Linear	A	–0.0092	0.0178
	Linear	B	0.0092	0.0178
	Linear	C	0.0100	0.0106
	Linear	D	–0.0017	0.6459

kept lower than a predetermined maximum amount of 0.01 mm.

After performing the predetermined experiments and feeding the results to Design Expert software, the regression coefficients that relate this geometric tolerance to the input factors were extracted and indicated in Table 7.

As indicated by Table 7, there is a linear relationship between input factors and geometric tolerance. Electric voltage, electrolyte flow rate, and concentration are the significant effective process variables. 3D plots of geometric tolerance as a function of input factors were made based on the extracted empirical model and represented by Figure 5(a) and (b).

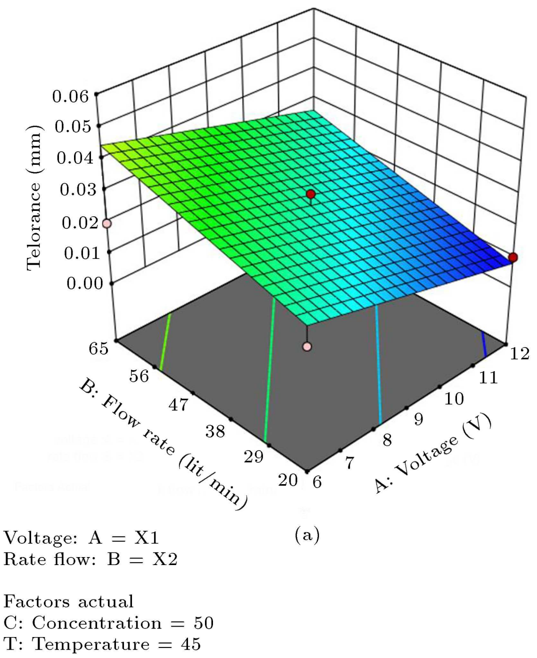
As indicated by Figure 5, an increase in electrolyte concentration and its flow rate leads to a linear increment in tolerance error. However, an increase in electric voltage has reduced the hole finishing tolerance. The increase of the electrolyte temperature slightly increased the tolerance. The most significant factor was the electrolyte flow rate.

The results of ANOVA for tolerance error are shown in Table 8. As shown in Table 8, a linear model could simulate the dependence of tolerance error on the input factors. This model had the smallest P-value and adequate precision.

5. Multi-objective optimization of the process

Maximizing the MRR, minimizing the surface roughness, and retaining the geometric tolerance error equal to or less than 0.01 were the purposes of multi-objective optimization. The optimization was conducted in Design Expert software based on the desirability approach. In defining the desirability function, we assumed that all three responses have the same significance.

Figure 6 represents the suggested values for the input parameters to attain an MRR of 0.87 g/min, average surface roughness of 2.31 μm, and a tolerance error of 0.01 mm. These outputs were achieved when the potential difference, electrolyte flow rate, electrolyte concentration, and electrolyte temperature were 12 V, 41.6 l/min, 37.3 g/l, and 60°C, respectively.



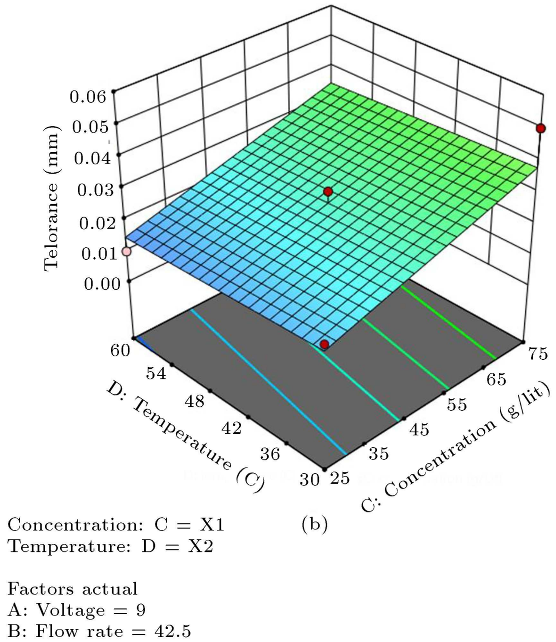


Figure 5. (a) Evaluation of tolerance as a function of voltage and flow rate; (b) effect of electrolyte concentration and temperature on tolerance.

Table 8. Results of Analysis of Variance (ANOVA) for geometric tolerance.

Source	Sequential P-value	Lack of fit P-value	Adjusted R^2	Predicted R^2	Precision adeq	
Linear	0.0039	0.1806	0.3975	0.2011	7.1870	Suggested
2FI	0.9752	0.1389	0.2268	–0.5714	—	
Quadratic	0.3184	0.1431	0.2837	–0.8689	—	
Cubic	0.2198	0.1702	0.6160	–6.0818	—	Aliased

The optimization has a desirability value of 89%, which indicates the high level of appropriateness of the optimum condition.

As shown in Figures 6 and 4, increasing the electric voltage, the electrolyte temperature, and concentration have resulted in an increase in MRR. An increase in electric voltage leads to enhancement of the electric current upon the Ohm's law. On the other hand, the MRR in electrochemical finishing could be estimated by Faraday's law, which may be written as:

$$MRR = \frac{Ia}{Fv}, \tag{4}$$

where MRR, I, a, F, and v are MRR, electric current, atomic mass, Faraday's constant, and electrochemical valance of atoms [1]. Accordingly, an increase in electric voltage results in an increase in MRR. Also, an increase in the temperature and concentration of electrolyte leads to an increase in the conductivity of electrolyte [17], and upon Ohm's law, the increase in the conductivity results in an increase in electric current. Hence, according to Eq. (4), the MRR increased.

Figure 6 shows that the increase in electric voltage and electrolyte flow rate has resulted in the reduction of surface roughness. Also, an increase in the concentration of electrolyte resulted in an increase in surface roughness. For analyzing these effects, it is helpful to compare the roughness profile of the workpiece surface before and after the finishing in the optimum condition. Figure 7 represents these two roughness profiles.

As shown by Figure 7 in the optimum condition of the finishing process, the average roughness of the workpiece has reduced from the initial value of 8.5 μm to the new value of 2.25 μm, and the final measured surface roughness is very close to the predicted roughness (2.3 μm) of the RSM model. The initial roughness profile of the workpiece before starting the finishing process may be schematically represented by Figure 8. The surface profile of the workpiece includes some valleys and peaks, and the average distance of peaks from the cathode is lower than the valleys. Thus, there

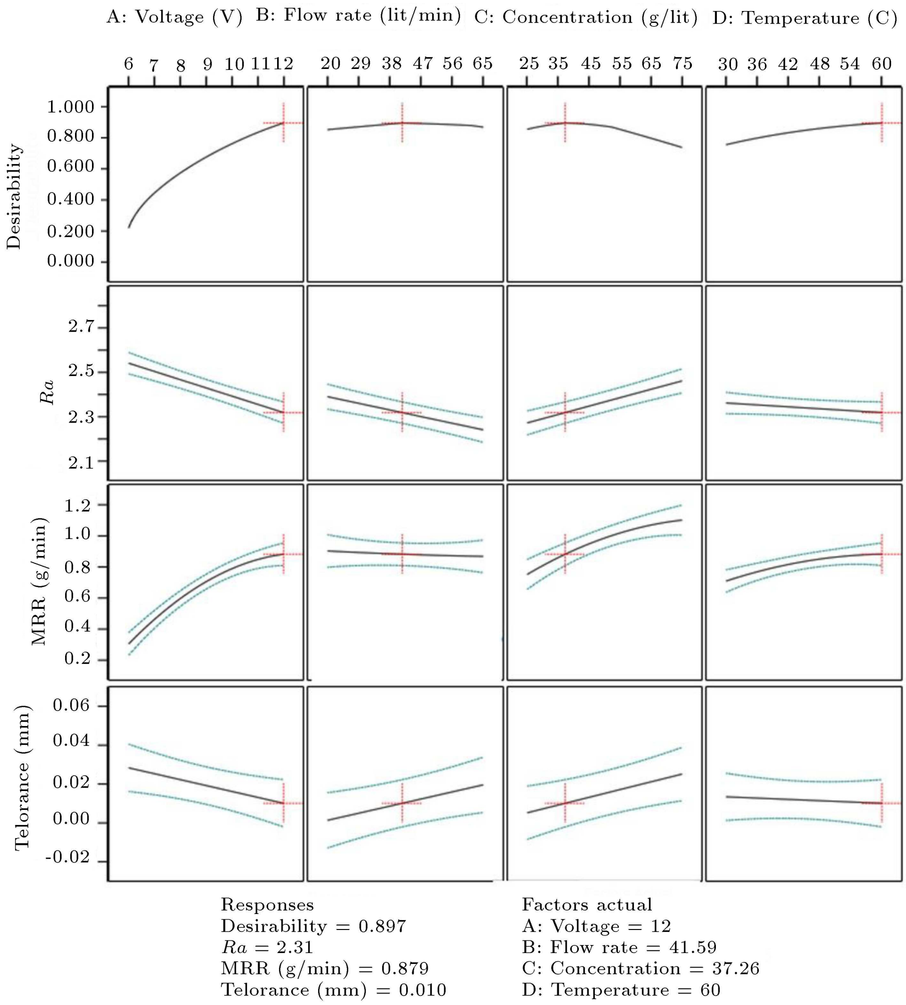


Figure 6. Optimization plots for the output variables.

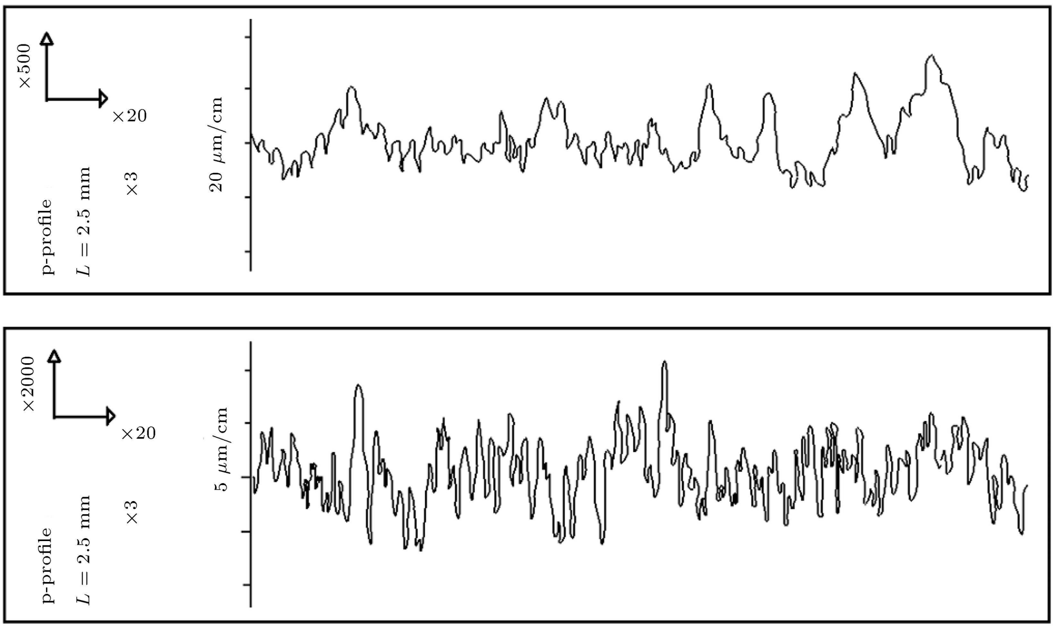


Figure 7. (a) Roughness profile before electrochemical finishing ($Ra = 8.5$ μm), and (b) roughness profile after electrochemical finishing ($Ra = 2.25$ μm).

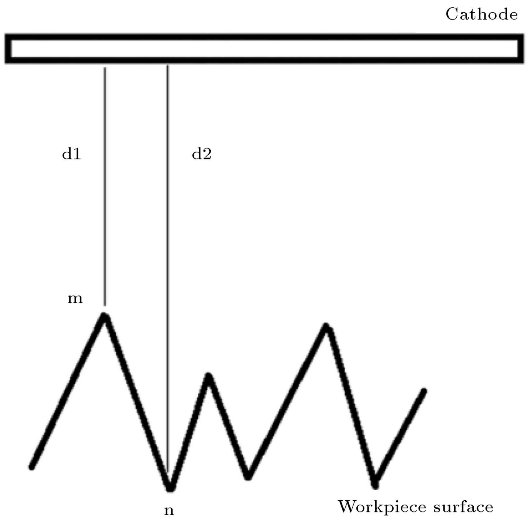


Figure 8. Schematic representation of the roughness profile of the workpiece before electrochemical finishing.

exists an Ohmic resistance difference between the two paths, and conductivity in the path (d1) is more than its value through path (d2), and one can write:

$$K_{mo} - K_{no} = +\Delta K, \tag{5}$$

where K is the electric conductivity in the scale of $(1/\Omega)$. Upon the Ohm's law, we have $I = KV$, and one can write:

$$I_{mo} - I_{no} = V(\Delta K) \rightarrow I_{mo} = I_{no} + V(\Delta K). \tag{6}$$

Eq. (6) shows that by increasing electric voltage, the electric current on the peaks becomes greater than the electric current on the valley, the peaks dissolve faster, and surface roughness is reduced.

6. Conclusion

In this article, the surface roughness of the inner hole of a CK45 steel bush was reduced by the electrochemical finishing process. Also, it was desirable to minimize the process time and to keep a predefined type of dimensional tolerance equal to or lower than 0.01 mm. To this, an experimental study was performed to evaluate the effects of process parameters on surface roughness, Material Removal Rate (MRR), and geometric tolerance. The design of experiments was carried out by Box-Behnken Design (BBD) in Response Surface Methodology (RSM). The empirical models which relate the input variables to the outputs were extracted and evaluated by Analysis of Variance (ANOVA). Finally, multi-objective optimization was performed to determine the optimum input parameters. It was shown that each input process parameter has a unique effect on the selected outputs. However, the electric voltage is the only process parameter whose enhancement results in the enhancement of the geometric accuracy, surface finish, and MRR simultaneously.

This article represented the application of multi-objective optimization in a manufacturing process. Using this kind of optimization, the necessary conditions for manufacturing the parts with a predetermined quality may be obtained. For example, in electrochemical finishing of the inner holes in CK45 steel bushes, for attaining an inner hole with a surface roughness of 2.3 μm and dimensional tolerance of 0.01 mm, with the maximum MRR, the voltage, electrolyte flow rate, electrolyte concentration, and its temperature should be 12 V, 41.6 l/min, 37.3 g/l, and 60°C, respectively.

Nomenclature

a	Atomic mass
A	Voltage
B	Flow rate
C	Concentration
Ci	Regression coefficients
D	Temperature
$D(y)$	Desirability of parameter y
F	Faraday constant
FW	Final Weight
I	Electric current
IW	Initial Weight
K	Conductivity
T	Machining time
v	Dissolution valance
X_i	Input parameters
Y_i	Output responses

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