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Experimental Investigation of Electrochemical Finishing Process Using Box-Behnken Design in Response Surface Methodology

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ABSTRACT: Electrochemical polishing is a nontraditional finishing process by which the surface roughness of the metallic workpiece is reduced due to anodic dissolution. In this process, an electrochemical cell is formed using the workpiece as the anode, a tool as the cathode, and a power supply. Different parameters like inter electrode gap, the chemical composition of the electrolyte, and its temperature along with the electric potential affect the finishing performance. The important performance parameters are surface roughness, material removal rate, and the dimensional tolerance of the workpiece. In this article, the effect of inter electrode gap, cathode geometry, tool feed rate, and electric potential on the process outputs are evaluated experimentally. Due to the high number of input and output variables and possible interactions between the input variables, Box-Behnken design in response surface methodology is selected for designing the experiments. The experimental models are evaluated by analysis of variance. Using the response surface methodology, the effect of input parameters on process outputs and the possible interactions between the input variables are extracted. Also, multi-objective optimization is performed for determining the input variables which are adequate for maximizing the material removal rate along with achieving a predetermined amount for surface smoothness and geometric tolerance.

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1- Introduction

Improving the surface roughness of metallic parts by electrochemical dissolution processes has been the subject of numerous research papers [1-3]. In the present paper, an experimental study is performed for modeling the final surface finish, geometric accuracy, and material removal rate in the electrochemical finishing of CK45 steel bushes. The experiments are designed by Box-Behnken design in response to surface methodology. The process input variables are electric voltage, cathode geometry, inter electrode gap, and cathode feed rate. The effect of input variables on the outputs and the interactions of input variables are determined. Finally, multi-objective optimization is performed for determining the input variables adequate for maximizing the material removal rate along with achieving a predetermined amount of surface smoothness and geometric tolerance.

2- Materials and Procedures

In this research, an electrochemical finishing machine tool was constructed which involved a DC power supply, a suitable tool holder and tool feeding system which could provide both linear and rotational movement of the tool, an electrolyte charging system, and a special fixture for holding the steel bushes. During the electrochemical finishing, the Inter Electrode Gap (IEG) almost remained fixed. The constructed setup was used for reducing the surface roughness of CK45 steel pipes. The electrolyte was NaCl solution which has high current efficiency and low price [4].

The constant process variables were electrolyte's temperature, concentration, flow rate, and finishing time which were $30\,^{\circ}\mathrm{C}$, 50 gr/lit, 45 lit/min, and 20 minutes, respectively. The cathode was made of brass and had three forms which are represented in Fig. 1.

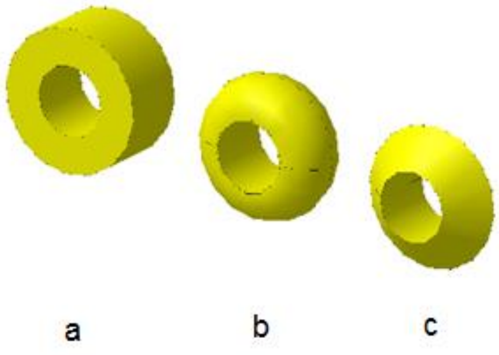

Fig. 1. Different cathode forms a: cylindrical form with rectangle cross section, b: cathode with circular cross section, c: cathode with triangle cross section

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Table 1. Factors and levels used in the Box-Behnken design

factors	levels		
Voltage (V)	6	9	12
Feed rate (mm/min)	10	15	20
IEG (mm)	0.5	1	1.5
Tool form	-1	0	1

Table 2. Analysis of variance (ANOVA)

outputs	source	*P*-value	Adjusted R^2	Predicted R^2
Ra	linear	$\leq$ 0.0001	0.7654	0.6902
MRR	quadratic	0.0018	0.9812	0.9502
Tolerance	linear	0.0010	0.4719	0.3164

3- Design of Experiments

In this experimental study, the output variables were Material Removal Rate (MRR), surface roughness (*Ra*), and geometric accuracy. The input variables were tool form, inter electrode gap, and the electric potential difference between the anode (workpiece) and cathode (tool). The design of experiments was performed by Box-Behnken design which is a spherical, revolving design and is matched with response surface methodology. This DOE procedure enables one to evaluate the effect of each input variable and its interactions on the output parameters. Also, the empirical mathematical models were extracted for determining the relation between the input variable with the output parameters.

Numbers -1, 0, and 1 were specified for each cathode form in Fig. 1 i.e. (a, b, c) respectively. The number of experimental runs was 27. For each experimental run, the surface roughness, material removal rate, and geometric tolerance were measured. The empirical models were extracted using response surface methodology (RSM) and with Design Expert software.

4- Results and Discussion

According to the RSM results, the average surface roughness (*Ra*) had a linear dependence on the four input variables. Eq. (1) represents this linear relationship:

$$
\begin{aligned}
Ra &= 1.127 - 0.018 \times A + 0.015 \times B + \\
&\quad 2.111 \times C - 0.295 \times D
\end{aligned}
\tag{1}
$$

where A, B, C, and D are voltage and cathode feed rate. IEG, and tool form respectively.

Material removal rate had a second order dependence on the input variables. Eq. (2) represents this non-linear relationship:

$$
\begin{aligned}
MRR &= -0.5 + 0.172 \times A - 0.028 \times B \\
&+ 0.083 \times C - 0.05 \times D + 0.001 \times A \times B \\
&+ 0.002 \times A \times D - 0.004 \times B \times C \\
&- 0.001 \times B \times D - 0.005 \times C \times D \\
&- 0.005 \times A^2 - 0.033 \times C^2 + 0.008 \times D^2
\end{aligned}
\tag{2}
$$

Eq. (2) shows that electric potential is the most significant variable in influencing the material removal rate. Also, there are some weak interactions between the input variables.

Geometric error (tolerance) is the last output parameter which is affected linearly by the input variables. Eq. (3) represents this linear relationship:

$$
\begin{aligned}
Tolerance &= -0.02 + 0.0025 \times A + 0.0008 \times B \\
&+ 0.0083 \times C - 0.0125 \times D
\end{aligned}
\tag{3}
$$

As given by Eq. (3) the tolerance, which represents the geometric error between the inlet and outlet diameters of the hole after the finishing process, was strongly affected by tool form.

Analysis of Variance (ANOVA) was performed for evaluating the accuracy and adequacy of experimental modeling. Table 2 represents the results of this analysis.

5- Multi-Objective Optimization

The targets of multi-objective optimization were maximizing the MRR and keeping the tolerance error and surface roughness equal to or lower than 0.01 mm, and 2 micrometers respectively. This optimization was performed in design expert software using the desirability approach. All three responses had the same importance. Fig. 2, represents the optimization plots for output variables. In the optimum condition, the electric voltage, tool feeding rate, Inter Electrode Gap (IEG), and tool form were 11.9V, 11 mm/min, 0.5 mm, and tool form 1 (with triangle cross-section) respectively. Also, in the optimum condition, the values of MRR, surface roughness, and tolerance were 2m , 0.72 gram/min, and 0.01 mm

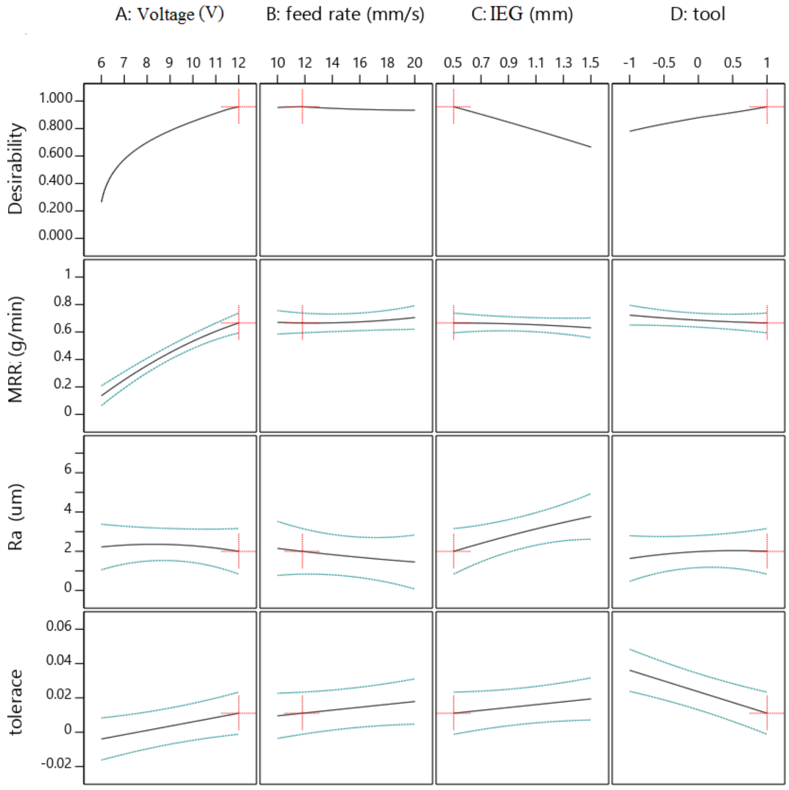

Fig. 2. Optimization plots for the output variables

respectively. The desirability of optimization was 89% which represents the high level of suitableness of the optimum condition.

6- Conclusions

In this investigation, the electrochemical finishing process was performed for reducing the surface roughness of the inner surface of CK45 steel bushes.

By employing response surface methodology the effects of electric voltage, tool form, inter electrode gap, and tool feeding rate on surface roughness, geometric tolerance, and material removal rate of finishing process were determined. The extracted empirical models provided a good explanation of the relationship between the input variables and the responses. Also, multi-objective optimization was performed for attaining the highest material removal rate along with predetermined limiting values for surface roughness and geometric accuracy.

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