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Prediction of surface roughness in electrochemical process of stainless steel 301 by response surface methodology

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Abstract

Electrochemical Machining (ECM) is an unorthodox technique for the removal of metals, which draws upon principles obtained from the field of electrochemistry. The technique relies on three essential components: an electrolyte, a workpiece, and a cathode tool. When an electric current flows, metal ions dissolve, leading to the elimination of material. (ECM) has been extensively utilized in several industrial sectors, notably in the production of components utilized in medical, aerospace, automotive, and general maintenance applications. The surface texture of the workpiece produced by electrochemical machining is influenced by a wide range of characteristics. The present study employs a research response surface technique to investigate the impact of key parameters, including current, electrolyte intensity, and gap, on the surface roughness of stainless steel 301 as a workpiece. The test utilized Minitab22 and the L27, which were created using the Taguchi orthogonal array. Each experiment utilizes distinct input values, and the outcomes are examined using analysis of variance (ANOVA). The optimal processing configurations and performance parameters are provided, with the conclusive testing outcomes and prediction model. The findings indicated that the predictive model exhibited an R2 coefficient of determination of 92.6%. This coefficient quantifies the capacity of the input variables to accurately forecast the output variables. The current of 80% was the primary factor in establishing the least surface roughness. The concentration of the electrolyte emerged as the subsequent crucial factor in setting the minimum surface roughness threshold of 15%.

Keywords— Response Surface Techniques, ECM, Surface Roughness, Taguchi method

1 Introduction

Electrochemical machining is a non-contact method in which the anode (the material) and the cathode (the tool) move steadily toward each other, and liquid electrolyte flows quickly across the space between them to remove the dissolved material. (Zhu et al., 2010). The advantages of the electrochemical machining method include the absence of burrs, a longer tool life, the absence of internal stress, and improved surface quality and material removal rates. The surface form of the workpiece is affected by the temperature generated while machining, which is dissipated on the cathode as a tool. This method is known as electrochemical machining and is based on the anodic solution process of electrolysis. Electrochemical machining differs from other cutting procedures because it does not require physical contact between the workpiece and the tool. The chip removal method is electrochemical, and the reaction responsible for this is electrolysis. (P.V.Jadhav et al., 2014) The operational mechanism of electrochemical machining (ECM) relies on the dissolution of anodic material at the interface

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between the surface of the workpiece and an electrically conductive solution without inducing any mechanical or substantial thermal effects on the workpiece surface.(Sharma & Patel, 2022)Operating parameters have an impact on the surface quality of a product. Hence, it is challenging to ascertain the optimal cutting parameters. These flaws are sufficient to render a model ineffective. Monitoring the surface roughness is a crucial component in developing an Artificial Neural Network (ANN) methodology to identify cutting factors that may be used in precise models.(Kanagarajan et al., 2007). studies of Electrochemical machining have been carried out over several years to offer data on the most efficient operation. In a productive study by Jain and Jain (Jain & Jain, 2007) optimized using real-code genetic algorithms, we can control the most important process variables are electrolyte velocity, applied voltage, and feed rate to reduce geometrical error subject to temperature, choking, and passivity constraints. Asokan & et al. (Asokan et al., 2008) used gray analysis to maximize the pace of material removal and reduce roughness. Chakradhar and Venugopal (Chakradhar, 2011) optimized material removal rate and surface roughness, cylindricity error, and overcut using gray relational analysis, taking into account electrolyte concentration, input voltage, and feed with three levels. Ibrahim (Ibrahim, 2017) The Taguchi theory was used to study the influence of different process factors on surface roughness and material removal rate, as well as the optimization of different process factors in Electrochemical machining. Muataz Hazza Faizi & et al. (Al Hazza, 2017) Electrode material affects MRR, EWR, and surface roughness in electro-discharge machining (EDM) (Ra). Copper, aluminum, and graphite electrodes are used in the EDM of AISI 304 stainless steel workpieces. The study employs kerosene as a dielectric fluid at 2.5A, 4.5A, and 6.5A. The response surface methodology was used to design and evaluate the complete factorial experiment (RSM). examined MRR and EWR. Current increasing replies. Eventually, the desirability function approach determined the best values. Ahsan &. et al. (KHAN & Al Hazza, 2018) Nickel powder mixed dielectric fluid was tested on mild steel EDM performance in this research. Process parameters include peak current, tool/electrode diameter, and powder concentration. Process performance is assessed by MRR, TWR, and surface roughness (SR). The experiment was developed using Design of Experiment (DOE) software's Complete Factorial. To enhance MRR and decrease TWR and SR, the study identified key process factors. 3.5 A and 6.5 A current, 14 mm and 20 mm tool sizes, and 0 and 6 g/l Nickel powder concentrations were used in the experiment. Before and after each run, the copper electrode and mild steel workpiece are weighed. The findings show that current has the greatest impact on MRR, TWR, and SR. The tool life and workpiece surface roughness improved using nickel powder in the dielectric fluid. MRR and TWR also rose with tool diameter. SR improved with tool diameter. Senthilkumar and Ganesan (Senthilkumar & Ganesan, 2018). Electrochemical machining (ECM) is used to reduce surface roughness and increase the metal removal rate in aerospace, automotive, and surgical components to maintain quality. Nhung & et al. (Nhung et al., 2020) studied the different Electrochemical Machining (ECM) process parameters that affect copper-based aluminum samples. To find the best values and how they affect surface quality, the system employs the Taguchi technique and signal-to-noise models, variance analysis, and regression analyses. The results demonstrate that the inter-electrode gap greatly impacts surface roughness and material removal rate. The material removal rate is maximized at a voltage of 100 mV, an inter-electrical gap of 0.5 mm, and an electrolyte concentration of 100 g/l. enhance productivity and surface roughness; the study recommends more investigation into these factors. Wang & et al(Y. Wang et al., 2020). The surface integrity of three γ-TiAl alloys is investigated in the study of electrochemical machining (ECM). Surfaces exhibit distinctive morphologies at low current densities due to intense localized corrosion. Nevertheless, the alloys display smooth surfaces when the current density is high. The roughness value of the extruded Ti-48Al-2Cr-2Nb material is the lowest, decreasing progressively with increasing current density. Yuan & et al. (Yuan et al., 2021). Large aero-engine TiAl alloy blades are lightweight and efficient, but their size and twisted profile make accurate manufacture difficult. Electrochemical machining (ECM) is best for these blades. Experiments suggest that low-frequency pulse ECM produces high-quality surfaces. Lui & et al(Liu et al., 2022) .The study suggested low current density electrochemical machining (ECM) at ambient temperature to remove the Haynes 214 honeycomb structure at the micron level. The $NaNO_3$ solution is chosen for its electro-dissolving stability, low dissolution resistance, and material removal rate of (1.5-7.5) $\mu m \cdot min^{-1}$.Senthilkumar (Senthilkumar, 2023) Metal matrix composites (MMCs) are becoming more prevalent in several sectors because of their lightweight nature and ability to withstand wear. Nevertheless, the process of machining MMCs might be difficult because of the abrasive characteristics of the reinforcing particles. Despite the complex relationship between parameters and responses, electrochemical machining (ECM) is employed for machining metal matrix composites (MMCs).

The response surface methodology is used to predict the most influential factors (current, electrolyte intensity, and gap) and optimize the response to these variables in the electrochemical machining process. An analysis and strategy for the experiment were carried out using the response surface technique. An array of statistical and mathematical tools for analyzing and modeling situations where many factors contribute to a single response of interest. This method uses a sequential experimentation technique to achieve optimality for that response for empirical model construction and optimization. Using experimental design and regression analysis, a near-optimal solution may be determined based on the response model. Optimization and characterization of processes are two common applications of the response surface technique While one of the main goals of employing the response surface methodology is to explore the response throughout the range of input parameters, another is to pinpoint the sweet spot in the space where the response is maximized, cautiously by analyzing the resultant model. The fuzzy logic model outputs were close to the experimental values. The dimensional study produced a semi-empirical surface roughness model. Using dimensional analysis, this mechanistic model predicts surface roughness beyond the major input factors. Experiments were performed, and sensitivity analysis was used to check measurement inaccuracies. Results showed that the current impacts of Ra are greater than those of other factors. The objective is to investigate the significant processing elements associated with electrochemical machining. The objective is to assess the surface roughness of stainless steel 301 and enhance the understanding and use of ECM and its many iterations. Furthermore, it provides novel insights into the technological expertise of ECM, which will be highly valuable in developing future engineering advancements in this field.

2 Fundamentals of Electrochemical Machining

Electrochemical machining is a technique that involves the use of electricity to remove particles from the workpiece. A chemical reaction takes place on the electrode, and the input voltage is used. Across the cathode & anode (the electrode), the substance is dissolved through the anode. In the method of electrochemical milling (Mishra et al., 2021).

3 Methodology Of Response Surface

The Response Surface Method (RSM) is a model used to analyze the impact of several variables on a set of response variables. (Senthilkumar et al., 2013). It is a method that involves conducting a series of experiments to construct and perfect an empirical model. Therefore, the methodology of response surface is a collection of statistical and mathematical procedures that are useful for analyzing and modeling a problem. And because the demand response is affected by a value of variables, the goal is to optimize the response to these variables. (Senthilkumar et al., 2013). In its most basic form, the mathematical model known as the second-order polynomial response surface model, which examines the effect of the parameters on the various response criteria, may be defined as follows:

$$Y_u = b_o + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x^2{}_i + \sum_{j>1}^{k} b_{ij} x_j x_j \tag{1}$$

Where k quantitative variables, X_i $(1,2,3, \dots, k)$ are code values, and Yu is the response. The constant values are interaction, linear, and quadratic to the prediction equation; a MINITAB22 package program was used to determine the coefficients of the equation depending on the regression model.

4 Experimental Procedure

Input current, electrolyte concentration, and gap used during electrochemical machine operation were analyzed to determine how they affected the machining product's desired machining quality characteristics and surface roughness. This was done using an electrochemical machine. The Electrochemical machine is shown in Figure 1.

Figure 1 shows the ECM cell that was used in these experiments. The drilling machine, the workpiece fixture, the electrolyte pump, and the power source are all parts of it. The drill It gives it a stable base and good control over how the tool moves, as well as can adjust the gap between the tool and the workpiece by hand. The fixture for the item is made of cast iron. Moves the solution in the reaction chamber so that there is a space between the tool and the workpiece. A DC welding machine with currents of 5A/10V to 400A/36V was used as a power source for the experiment.

Stainless steel 301 was utilized as the material for these tests and investigations. This alloy is widely utilized in the manufacture of vehicles as well as in the aerospace industry because of its excellent wear resistance, strong strength-to-weight ratio, and significant corrosion resistance. As can be seen in Figure 2, copper was used in these tests both as a tool electrode material and as a cathode. It is designed to be in the shape of a circle so that it can cut cavities in the workpiece using the same profile shape.

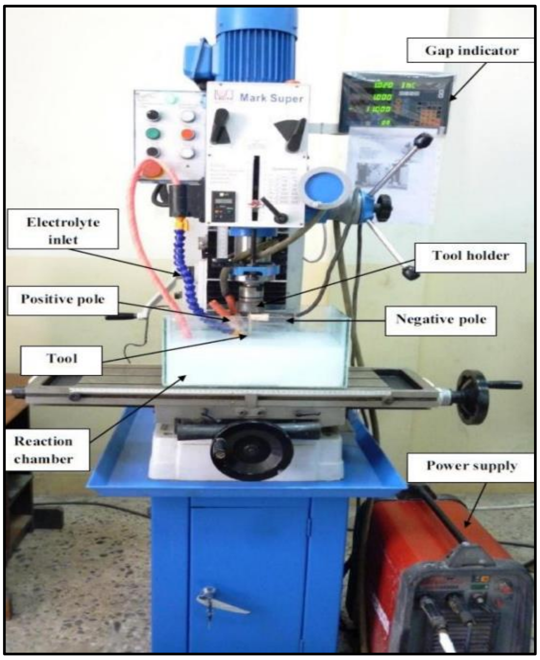

Figure 1: Electrochemical machine system part.

Figure 2: Tool used in experimental work.

The results of tests done at the Central Organization for Standardization and Quality Control on the chemical makeup of the material of the workpiece and the tool are shown in Table 1, Table 2, and Table 3. Standard alloy was purchased, and the examination was conducted in the Central Agency for Standardization and Quality Control laboratories, which gives a range of elements that is consistent with Standard 301.

Table 1: The Composition of (stainless steel 301)

Elements	**C%**	**Si%**	**Cr%**	**P%**	**S%**	**Mn%**	**Ni%**
Austenitic chromium-nickel stainless steel	0.13	9.80	17.04	0.015	0.005	0.49	6.27

Table 2: The mechanical properties (stainless steel 301)

Property	**Annealed Condition**
Tensile Strength	515-1100 Mpa
Yield Strength	250 Mpa
Elongation	40%

Table 3: The Composition of (Copper)

Elements	Zn%	P%	Sn%	As%	S%	Cd%	Pb%	Si%	Bi%	Ag%	Sb%	Cu%
Weight%	0.003	0.005	0.010	0.008	0.004	0.001	0.004	0.013	0.006	0.002	0.009	remain

The electrolytes that were utilized in the experiment were fresh solutions of sodium chloride (NaCl) that had various concentrations of the electrolyte. The tests were carried out with a variety of components, and the data gathered from them was recorded. A device that is used after each test to compare the findings is the one that measures the surface roughness. Table 4 presents an exhaustive account of the conditions under which the tests were carried out.

Table 4: Input Parameters of ECM

Parameter	Current (Amp), A	Electrolyte concentration (g/l), B	Inter-electrode gap(mm), C
1	40	40	0.5
2	80	60	1
3	120	80	1.5

5 Results And Discussion

The 12 tests are being carried out as shown in Figure 3, and Table 5 presents the results of the surface roughness measurements taken using Mahr Pocket Surf PS1 Portable Surface Roughness device as shown in Figure 4, and Table 6 from the design matrix. to examine the data, the degree to which the model is a good fit, as well as other tests such as those to determine whether or not the model is a good fit, whether or not it is a poor fit, and whether or not the model coefficients have statistical significance. There is going to be an analysis of variance done.

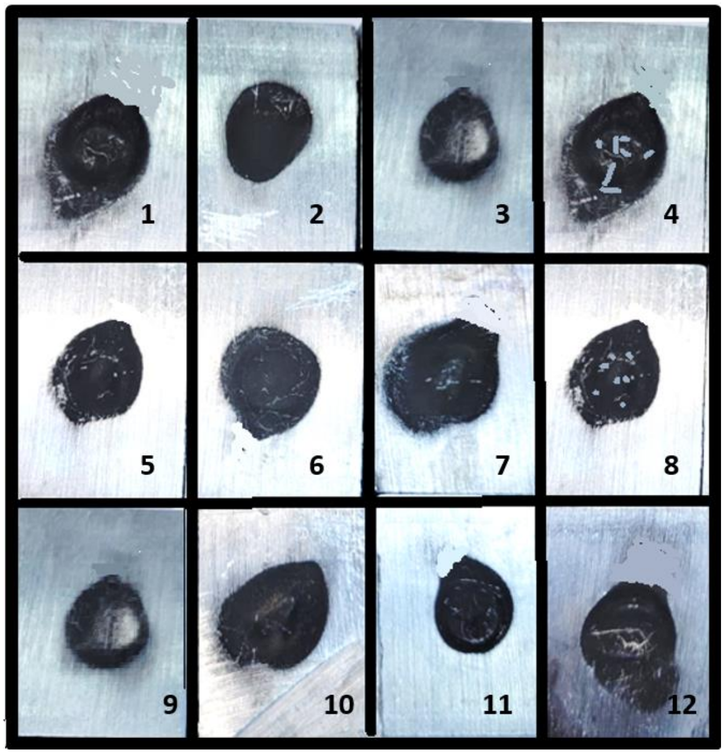

Figure 3: The experimental work sample.

Table 5: Output According to RSM

No.	Current	Electrolyte	Gap (mm)	Ra measured	Ra predicted
1	40	40	0.5	1.39	1.3904
2	40	60	1	1.43	1.4584
3	40	80	1.5	1.46	1.4848
4	80	40	1.5	1.34	1.3608
5	80	60	1	1.51	1.5232
6	80	80	0.5	1.40	1.38
7	120	40	1	1.55	1.5368
8	120	60	1.5	1.29	1.304
9	120	80	0.5	1.34	1.3736
10	40	40	1.5	1.39	1.3464
11	80	60	0.5	1.37	1.3752
12	120	80	1	1.57	1.5528

Figure 4: Mahr Pocket Surf PS1 Portable Surface Roughness Tester.

Table 6: Mahr Pocket Surf PS1 Specifications

Parameters (24, with tolerance limits)	Ra, Rq, Rz corr. to Ry (JIS), Rz (JIS), Rmax.
Traversing length (MOTIF)	1 mm, 2 mm, 4 mm, 8 mm, 12 mm, 16 mm
Calibration function	Dynamic
Dimensions	140 mm × 50 mm × 70 mm

The quadratic model is recommended since it has a statistically significant effect on the analysis of Ra. Table 5 presents the findings that may be seen about Ra. The R^2 values adjusted R^2 are 92.6%. The indicates with use regression mathematical model provided a satisfactory explanation of the connection that exists between the response surface roughness. The p-value that is associated with the model is not more than 0.05. (95% confidence) is a statistically significant indicator, which means that the model is valid. According to the results of the analysis of variance (ANOVA), which are presented in Table 7, it is possible to conclude that the current, represented by the value (A), is the factor that has the greatest influence on the minimum Ra, while the electrolyte concentration, represented by the value (B), is the factor that has the next greatest influence on the minimum surface roughness.

Table 7: ANOVA for surface roughness

Source	D.O.F	S-S	Mean	P%
Current (A)	3	0.0024	0.0008	80%
Electrolyte concentration (B)	3	0.082412	0.027471	15%
Inter-electrode gap (C)	3	0.015913	0.005304	5%
Error	2	0.0095	0.0047	
Total	11	0.129		100%

It was the RSM tool, which uses the Minitab package, that made the statistics model. The surface roughness was used to give the value (0, 1, etc.) from the applied RSM in the Minitab package, and that value was placed into Equation 2. To forecast the surface roughness, this equation was used, and from it, the functions that would represent the predicted surface roughness were derived:

$$Surface\ roughness = 1.29 + 0.007X_1 - 0.017X_2 + 1.31X_3 - 0.00002X_1^2 + 0.0001X_2^2 - 0.736X_3^2 - 0.000002X_1 * X_2 - 0.0017X_1 * X_3 + 0.0066X_2 * X_3 \quad (1)$$

The surface roughness that was anticipated. In addition, it was clear that the gap (x3) was the most important machining parameter and had the greatest effect on surface roughness in Equation 2. Figure 5 displays the link between the anticipated and measured values of Ra. This demonstrates that the efficiency response surface methodology uses a multiple regression model to predict the values of the variables. Display the probability drawing of the residual response for Ra in Figure 6. A check on this plot in Figure 7 reveals some interesting information.

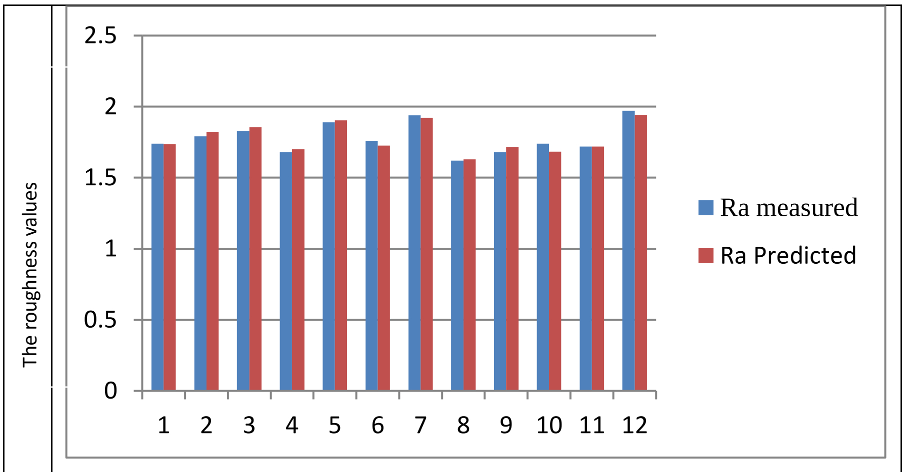

Figure 5: Bar chart of the surface roughness measured Vs predicted.

Figures 7 – 10 clarify the effects of current, electrolyte, and gap on the resultant surface roughness. It is noted that increasing the current increases the surface roughness; this means that the low current improves the surface roughness. Meanwhile, the rise in the electrolyte and gap to level two increased surface roughness.

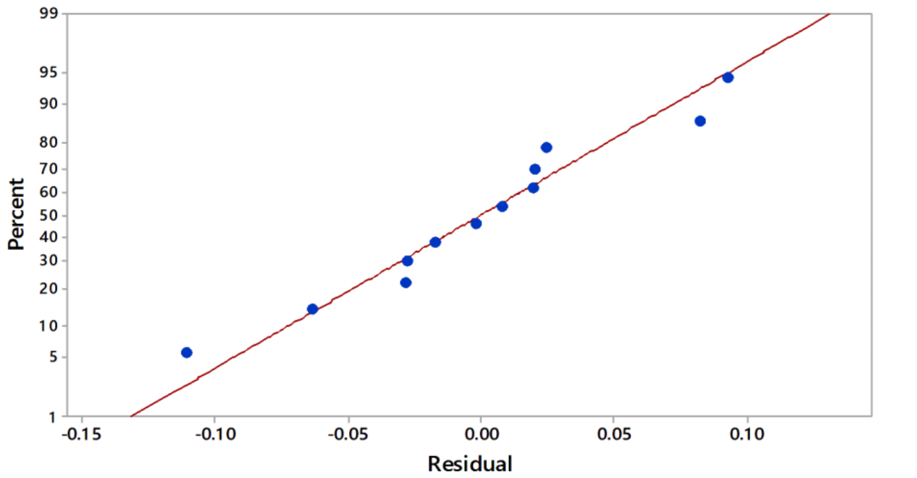

Figure 6: Probability of roughness

Sample number

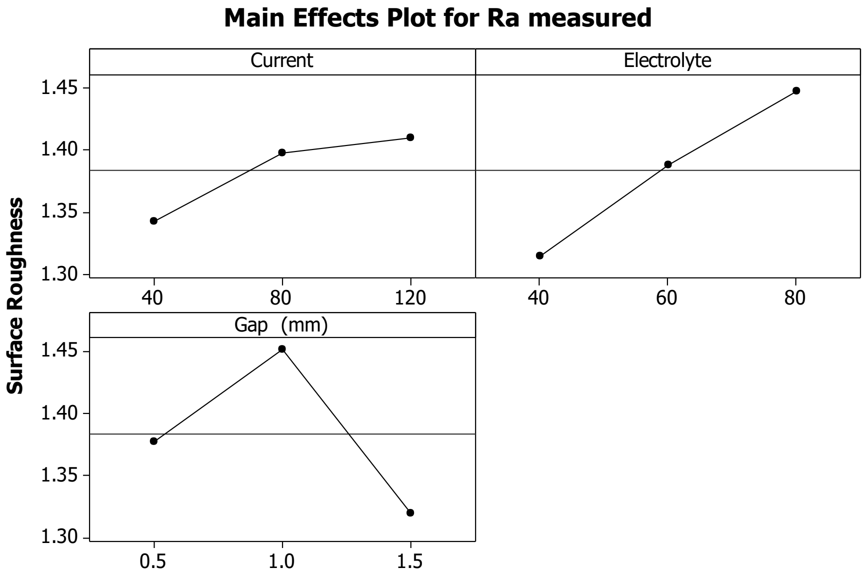

Figure 7: mean effect plot

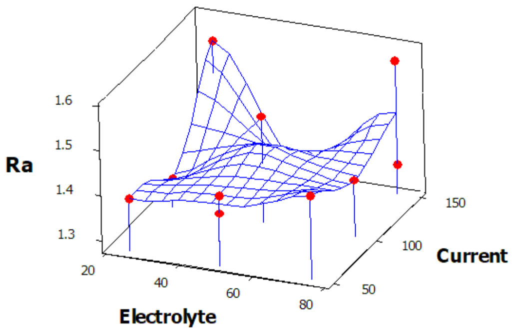

Figure 7: Current and electrolyte Effect on surface roughness.

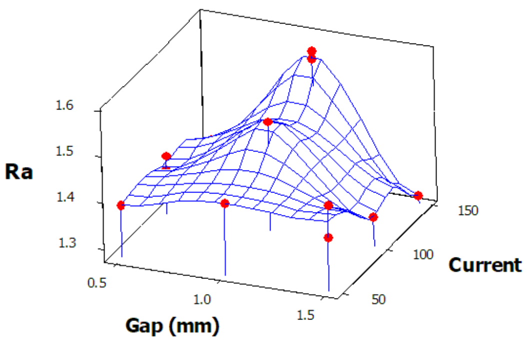

Figure 8: Current and Gap Effect on Surface Roughness

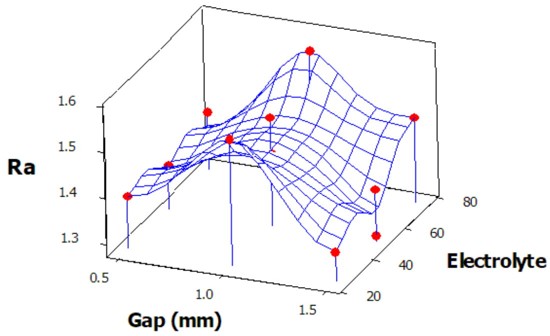

Figure 9: Gap and electrolyte Effect on surface roughness

Figure 11 shows that the Ra increases from (1.37 to 1.57)when the Current is raised from 40 to 120 amp. Rougher surfaces are produced by increasing the current density, increasing the Material Removal Rate (MRR) in Electronic Composition Material (ECM). Surface roughness may also be caused by overcutting when material is removed beyond the required form. Achieving the required dimensional precision and surface quality relies heavily on controlling the current density.

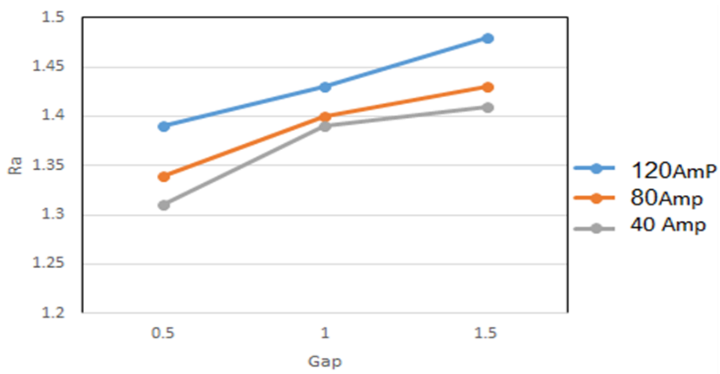

Figure 10: Gap and surface roughness (Ra)

This finding aligns with the information shown in Table 4, indicating that the Ra value rises as the Current increases while considering the influence of the electrolyte effect. The rationale is that an increase in current leads to a corresponding increase in kinetic energy, enhancing the Ra. Based on the chart and table you mentioned, it is evident that the highest Reich Ra value was seen in sample No. 2. Nevertheless, it is crucial to acknowledge that the optimal Ra value for a particular experiment may not always align with the optimal Ra value for other experiments or under varying conditions, as indicated by the chart or table displaying the Ra values for different samples. Based on the data supplied, it can be inferred that the experiment yielded a positive correlation between the variables Current and Ra. In alternative terms, a rise in the Current resulted in a corresponding increase in Ra. Several articles have been written that investigate the current's impact on the surface roughness that occurs during the electrochemical process. Wang et al. discovered that modifying the settings of electrochemical polishing may dramatically improve surface roughness, bringing it down to one-tenth of the value that was initially attained from milling procedures (G. Wang et al., 2020). In their study, Anderson and colleagues found that surface roughness increased when the electrochemical current or reaction time was increased. This was attributable to an increase in ion transfer (Anderson et al., 2017). Ngo et al. focused on optimizing process parameters in electro-chemical machining and discovered that the surface roughness of stainless steel may be minimized by applying the surface response approach (Ngo et al., 2020).

6 Conclusions

1. An accurate approach for predicting surface roughness was developed by adjusting the current, concentration, and intel electrode gap while using Minitab packaging.
2. R^2 measures how well the input variables can predict the output variables. It is 92.6% for this model.
3. The currents have the greatest influence on the minimum Ra, and the electrolyte concentration has the second-greatest influence on the minimum Ra.
4. An increase in the distance between the electrodes will increase the surface roughness of the workpiece.
5. The current parameter had the largest effect in the process with 80%, and the Inter-electrode gap was less effective with 5%
6. The best parameter to get minimum surface roughness is the current (100) electrode (50) gab (1mm). Equation 2 was applicable under identical circumstances.

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