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Enhancing surface integrity of 316 SS with ecofriendly electrolyte in electrochemical machining

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ABSTRACT

Electrochemical machining (ECM) is an advanced technology that enables the efficient and precise machining of difficult metal materials without affecting their mechanical properties or causing thermal stress. In this research, ECM was used for machining 316 stainless steel; it is recognized for its high corrosion resistance, tolerance to harsh chemical environments, and biological stability, making it ideal for use in surgical instruments, sutures, and implants. The development of eco-friendly electrolytes has the potential to impact the safety and performance of electrochemical devices. The development of eco-friendly electrolytes remains a challenging task for good operability. In this research, the possibility of using eco-friendly acidic sodium nitrate solution electrolyte in the ECM of SS316 was investigated. The experimental results manifested that using ECM with SS316 achieves effective results in terms of material removal rate and surface roughness. The results showed that the voltage was the sturdiest affecting parameter, followed by acidified sodium nitrate concentration on material removal rate (MRR), as well as for the surface roughness (SR). It was found that higher material removal rate (0.0823) was achieved with voltage of 30 V, electrolyte concentration of 100, and gap of 0.2 mm. Besides, the lowest surface roughness (0.1881 µm) was achieved with voltage of 30 V, electrolyte concentration of 125, and gap of 0.3 mm.

Keywords: electrochemical machining, stainless steel, ecofriendly electrolyte, Taguchi design, material removal rate, surface roughness.

INTRODUCTION

Electrochemical machining (ECM) is unconventional technique utilized for shaping steel and other conductive substances [1]. It is capable of machining intricate profiles and forms [2]. Electrochemical machining affords numerous possibilities to meet the requirements in diverse manufacturing sectors [3]. In this machining process, the material is removed chemically [4]. The workpiece acts as anode and the tool acts as cathode being alienated utilizing an electrolyte solution [5]. In the case of mainly challenging elements, electrochemical effect united with many effect on work material such as grinding effect (ECG) is applied, it is a kind of a hybrid procedure [6]. Also, the benefits of such a method are apparent: no wear of tool (cathode) [7]. ECM is founded upon the electrolysis procedure. Such a procedure of machining utilizes electrolytes, like sodium chloride (NaCl) and sodium nitrate ($NaNO_3$) aqueous solutions. Furthermore, the anodic dissolution resolution and correspondingly achieved accuracy [8]. ECM has limitations considering poor stock removal rate [9]. Moreover, because a custom-made tool has to be designed for every sole geometry of the constituent, ECM is characteristically merely economical for mass production [10]. Jeykrishnan et al. utilized brine solution (NaCl) as an electrolyte to discover the significant parameter affecting the response in electrochemical machining of D3 die steel [11]. Dhiraj Kumar and Sharifuddin Mondal used potassium chloride as an electrolyte due to its non-passive nature for electrochemical machining of the EN-19 tool steel with cylindrical shaped copper tool [12]. Khan et al. have found that NaNo3 exhibited the virtuous outcomes upon the surface roughness (SR) as well as the radial overcut (RO) [13]. Geethapriyan et al. investigated the influences of varied input procedure parameters upon the accuracies of machining in the procedure of electro-chemical micro-machining beneath (2) various NaCl and $NaNO_3$ electrolytes. NaCl was obtained to possess an elevated material removal rate (MRR) in comparison to $NaNO_3$ as an electrolyte. A superior SF and the RO were performed with $NaNO_3$ in comparison with the electrolyte of NaCl [14]. Nhung et al. have inspected the effects of (voltage, electrolyte concentration, feed rate, and gap) of ECM process on aluminum workpieces using NaCl electrolyte solution [15]. Liu et al. investigated the electrochemical conduct of typical austenite stainless steel (SUS316L), dual-phase stainless steel (2205 DSS), martensite stainless steel (SUS440C), and ferritic stainless steel (SUS430) in neutral solutions. The relationships between MRRs and stainless steel (SS) metallographic phases were also demonstrated, which give a viable notion to optimize the complements of the composition of the electrolyte and the workpiece of SS [16]. Shi Hyoung Ryu investigated the eco-friendly ECM features for milling and drilling SS employing micro foil and microwire electrodes into the electrolyte of citric acid [17].

The previous studies have shown that the selection of the appropriate electrolyte for the electrochemical machining process is limited to its operability, and there is no direct attention to the nature of electrolytes and their impact on the environment. Therefore, a search for sustainable and eco-friendly electrolytes for ECM is of utmost importance to produce a safer environment. This study focused on selecting non-toxic, sustainable, eco-friendly electrolytes to reduce the environmental impact. As well as one that yields good outputs, such as material removal and surface roughness.

EXPERIMENTAL SETUP

Materials and methods

This work highlights the importance of using ECM, as this technique relies on the principle of anionic dissolution of the metal without mechanical contact between the tool and the workpiece, allowing for smooth and precise surfaces that meet the required medical specifications. Electrochemical machining of stainless steel 316 was investigated. The chemical composition of SS316 is depicted in table 1. Alloy 316 withstands the atmospheric corrosion and the moderate oxidizing as well the reducing atmospheres. Also, it withstands the alloy corrosion into the contaminated marine environments. In addition, the alloy gives a brilliant resistance to the inter-granular corrosion at the welded state. Further, the alloy 316/316L possesses a brilliant toughness and strength at cryogenic temperatures [2]. The workpiece had dimensions of 15×15 mm and thickness 2 mm. As shown in Figure 1: (a) represents the workpiece before machining and (b) represents the workpiece after machining. A copper rod with a radius measuring 10 mm and length of 60 mm was employed, as shown in Figure 2. Cu offers a better surface finish. Moreover, Cu exhibits specific tasks to the biomedical alloys, like improving the mechanical properties through solution strengthening, giving antibacterial properties, and enhancing the resistance to biocorrosion [18]. The present research introduced an ecologically friendly, elevated exactness, as the electrolyte into the ECM is a critical factor; it gives the circumstances required for the reactions to take place. Also, the perfect electrolyte has to be cheap, noncorrosive, and less viscos, and possess elevated conductivity. In this work, a mixture of sodium nitrate ($NaNO_3$) and boric acid (H_3BO_3) was utilized. The boric acid was supplemented to the standard $NaNO_3$ electrolyte. Acidic sodium nitrate solution (0.05 of H_3BO_3+$NaNO_3$) of variable concentration was utilized as an electrolyte. Boric acid is weakly acidic and environmentally benign in low concentrations, by adding a small amount of boric acid, better surface finish is provided, and less stray corrosion is ensured.

An electrochemical cell was mounted, and a copper tool electrode clamped on a drill chuck was located above the electrochemical cell and a power source. The positional relationship of the tool electrode is that the copper rod electrode faces the SS316 plate workpiece. A servo mechanism

Table 1. Chemical composition of SS316

Element	Fe	C	Mn	Si	P	S	Cr	Mo	Ni	N
%	balance	0.08	2	0.75	0.045	0.03	18	3	14	0.1

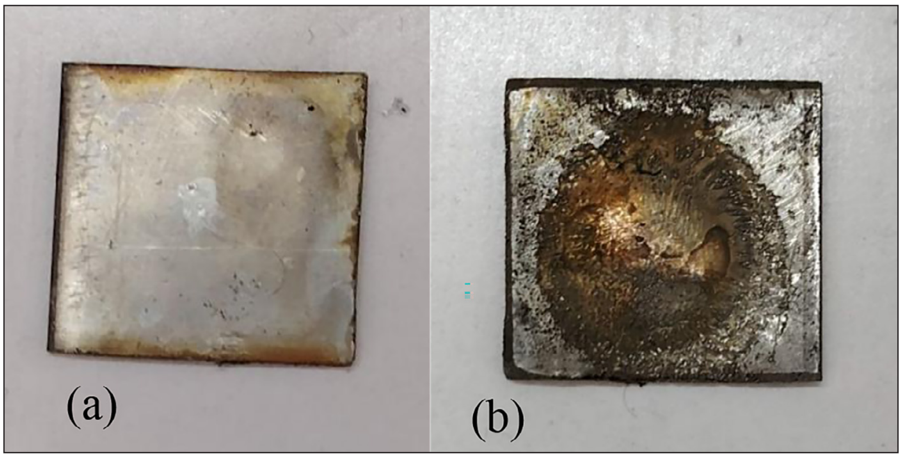


Figure 1. 316 stainless steel workpiece before and after machining

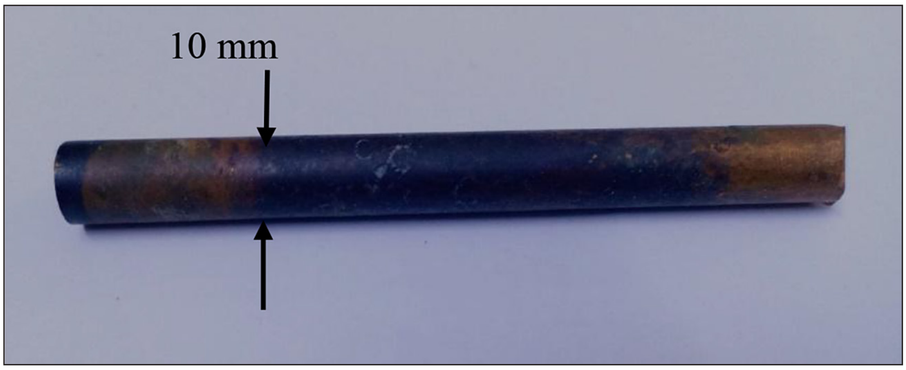


Figure 2. The copper rod tool used in electrochemical machining

is used to achieve the extremely small feed rates. A commercially available glass was used as the electrolyte tank. The tool was carried close to the job with the aid of press buttons offered upon the panel of control and the arrangement of table-lifting, keeping a specific gap, as shown in the schematic diagram in Figure 4 shows the power supply used, and Figure 5 shows the ECM cell. Furthermore, the current study includes three controllable parameters, such as the inter-electrode gap, the voltage, and the concentration of electrolyte. Three levels with three procedure factors were employed for the machining.

Design of experiment

In the current study, L27 orthogonal arrays (OA) was employed in the Taguchi design method with Minitab software support for conducting the experimentations. Numerous trials and errors were performed, and eventually, the MMR and SR were computed. It is essential to reduce variability and promote quality [19]. The factors of machining and their factor level are listed in Table 2. Also the investigational study processes throughout 27 runs with 3 levels were selected to determine the experimentations sequence. The factors such as voltage, gap, and electrolyte concentration have been selected in this work as the most affecting parameters in ECM process according to the preceding studies. Also, the selection of the levels have been made upon the previous studies and the initial experiments. Taguchi method offers a number of run fewer compared to the full factorial design [20, 21]. Additionally, in every process of machining process, MRR and SR are the significant factors regarding the tribological and economical points of view [22]. Orthogonal arrays are used in these approaches, which decrease the investigational runs for determining the influence of every parameter upon the output. Signal-to-noise ratios (S/Ns) were computed for every experimentation. For the situation to minimize the performance feature, the subsequent (S/N) ratio definition can be employed. Also, the outcomes

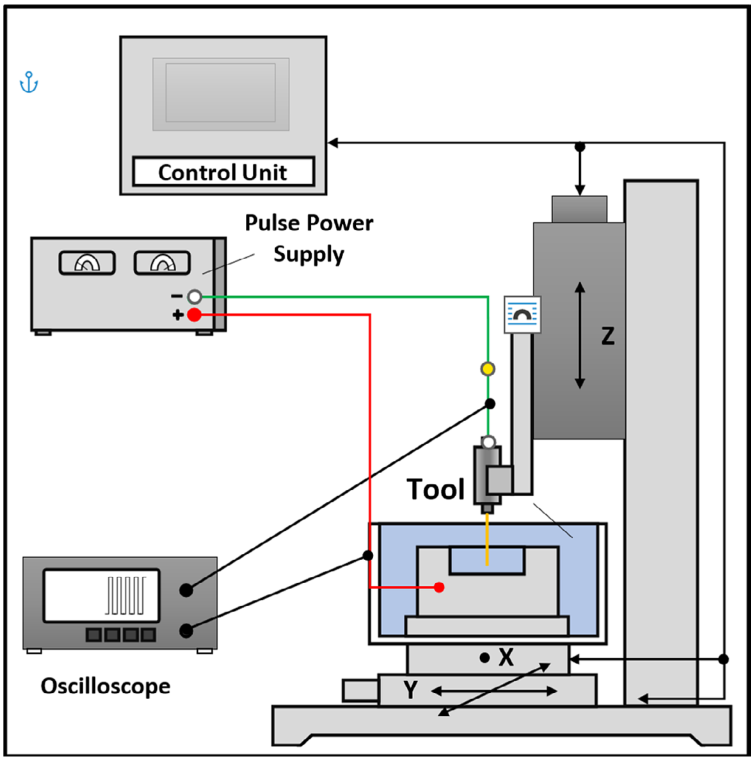


Figure 3. Schematic diagram of the experimental system set-up for ECM

Figure 4. The power supply utilized in the experiments

were scrutinized via the analyses of main effects, and (S/N). Eventually, a confirmation test was conducted for comparing the investigational outcomes with the assessed outcomes.

The Taguchi single-objective optimization technique was used for obtaining the optimum ECM process factor setting. Confirmation experimentations were achieved for validating the optimum process parameters setting for achieving the minimum value of SR. Table 2 depicts the Taguchi design matrix for the used input factors (voltage, EC, and IEC) and outputs (SR and MRR).

RESULTS AND DISCUSSION

Parametric analysis on MRR

The investigational results of the 27 experiments on 316 SS using a mixture of sodium nitrate ($NaNO_3$) and boric acid (H_3BO_3) as an

Figure 5. Electrochemical machining cell

Table 2. Taguchi design matrix for the used input factors and outputs

No.	Voltage (V)	EC (g/l)	IEG (mm)	SR (µm)	MRR (g/min)
1	10	75	0.2	0.4530	0.0551
2	10	75	0.2	0.4330	0.0532
3	10	75	0.2	0.4370	0.0470
4	10	100	0.3	0.4110	0.0577
5	10	100	0.3	0.3990	0.0587
6	10	100	0.3	0.4010	0.0569
7	10	125	0.4	0.3000	0.0573
8	10	125	0.4	0.3120	0.0569
9	10	125	0.4	0.3080	0.0570
10	20	75	0.3	0.3400	0.0592
11	20	75	0.3	0.3170	0.0623
12	20	75	0.3	0.3530	0.0633
13	20	100	0.4	0.2650	0.0592
14	20	100	0.4	0.2490	0.0611
15	20	100	0.4	0.2300	0.0605
16	20	125	0.2	0.2610	0.0702
17	20	125	0.2	0.2590	0.0688
18	20	125	0.2	0.2550	0.0691
19	30	75	0.4	0.2210	0.0620
20	30	75	0.4	0.2300	0.0575
21	30	75	0.4	0.2430	0.0541
22	30	100	0.2	0.2510	0.0823
23	30	100	0.2	0.2390	0.0811
24	30	100	0.2	0.2400	0.0799
25	30	125	0.3	0.1910	0.0720
26	30	125	0.3	0.1881	0.0665
27	30	125	0.3	0.2110	0.0695

ecofriendly electrolyte and studying its effect with the most important process parameters on the efficiency of the electrochemical machining process shows that the voltage was the sturdiest affecting parameter upon the MRR for acidified sodium nitrate. The voltage effect upon the MRR for various specimens is depicted in Figure 6. Also, from the plot, it is obvious that MRR is proportional to the voltage change rate [23]. As the potential difference between the copper electrode and the SS316 workpiece is low, a minimum MRR is obtained from the workpiece. While the increase in voltage values led to a rise in MRR, since the mass dissolved quantity is directly proportionate to the flowing electricity offset in accordance with Faraday's laws, into the middle of processes that will surge the chemical reactions at the elevated current values, giving superior outcomes [24].

Moreover, regarding the concentration of $NaNO_3$ and H_3BO_3 electrolyte, the supreme removal of material took place at 100 g/L and 125 g/L concentrations. Additionally, this can be ascribed to the rise in the electrolyte electrical conductivity with a rise in the concentration**.** Furthermore, at an elevation concentration, a large number of ions collected into IEG, in which the reaction phase at this stage was lagging and thus enhanced the chemical etching of the work material. The very low electrolyte concentration produced a minimum material removal due to the lack of ionic particles present in the electrolyte, which led to a lack of chemical reactions and a low chemical etching rate.

Along with this, the relation of MRR with IEG has been recognized to be inverse, as revealed in Figure 7. The gap acts as critical part in ECM. Also, in this process, there is no straight bodily contact between work material and Cu electrode, the material removal occurred due to the chemical reactions conducted into the existence of an electrolyte being circulated between the workpiece and the tool. Thus, setting the right gap is a significant parameter for producing elevated removal of material from the workpiece. In the experimentation of present work, the max. removal of material could be determined from the gap having a 0.2 mm optimum value. Only

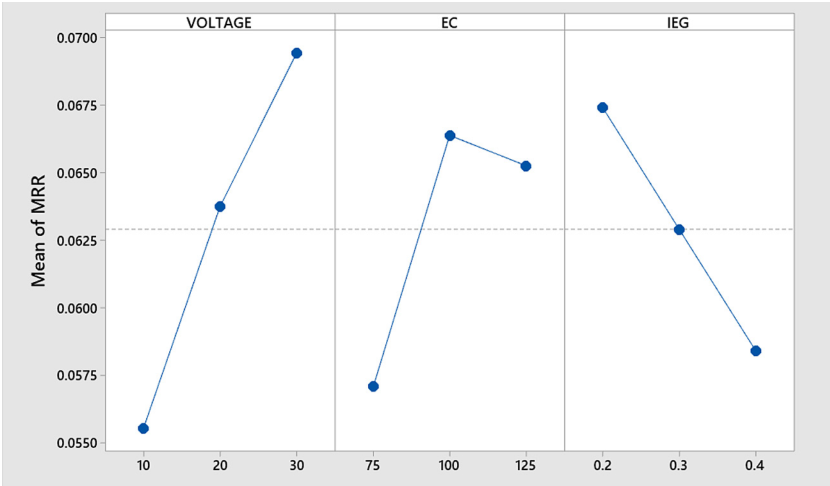
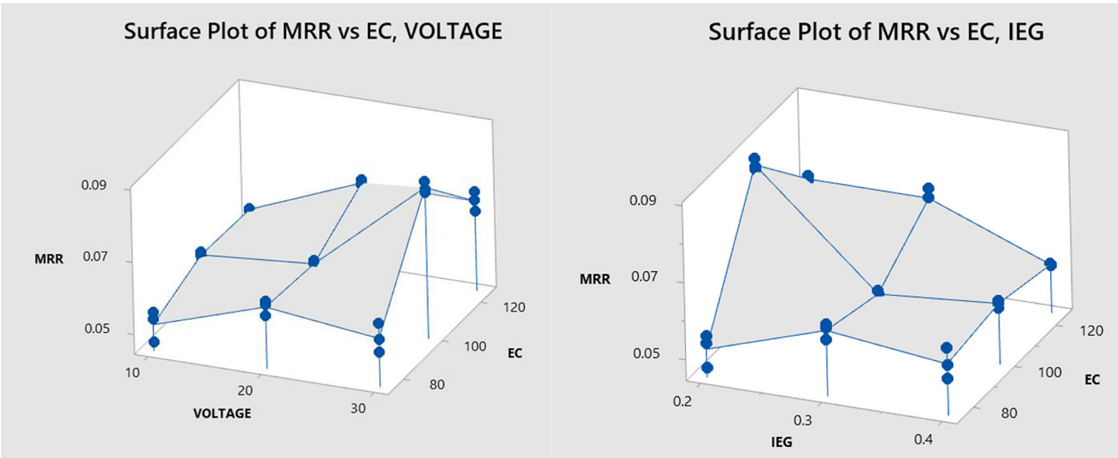


Figure 6. Main effects plot for MMR



(a) (b)

Figure 7. Parametric trends for MRR with Acidic sodium nitrate concentration: (a) voltage (b) inter electrode gap

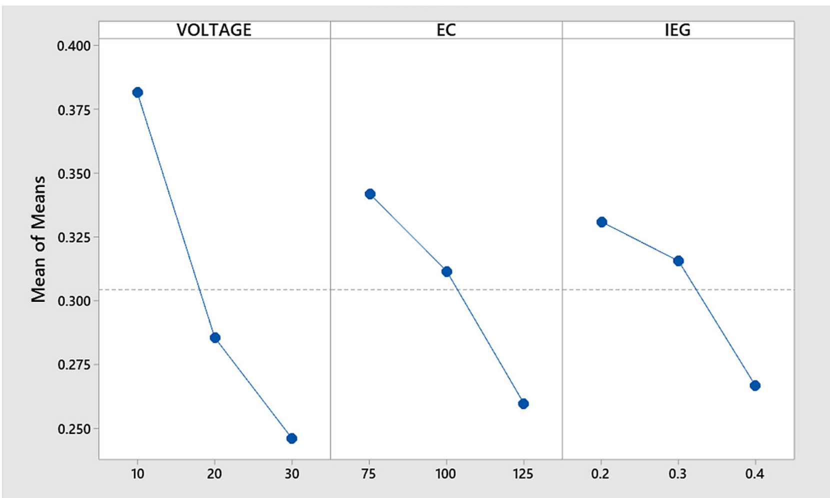


Figure 8. Main effects plot for means

the min. material quantity was removed from the workpiece at a 0.4 mm gap [12]. When the gap is max., then a reaction lack will be performed between workpiece and tool, and the min. MRR will be determined in workpiece.

In both interactive plots in Figure 6, the concentration of acidic sodium nitrate evinces similar trends along with the voltage and the inter electrode gap. EC with 100 g/l gives a higher material removal rate with a voltage value (30 V) and an interelectrode gap of 0.2 mm.

Parametric analysis on SR

The measurements of surface roughness for the 27 electrochemical machined workpieces during experiments using a mixture of $NaNO_3$ and H_3BO_3 as an ecofriendly electrolyte and study its effect with the record vital process parameters shows that the voltage effect upon the SR for SS316 is manifested in Figure 8. It has been realized that when the voltage is low, a poor surface roughness will be obtained. As, at high voltage values, the surface roughness declines, this is due to the elevated voltage fetching further electrical current as well as a sturdier electrical field cross the gap of the electrode; therefore, the electrochemical erosion quantity is larger [25]. The rise in the intensity of current led to a rise into the ions movement connected with the process of machining into the zone of machining, leading to a rise in electrochemical erosion, in which led to a better surface finish.

The resulting SR at the various concentration levels of acidic sodium nitrate for chosen specimens is elucidated in Figure 8. There, SR and the concentration of electrolyte are inversely proportionate to each other. As the electrolyte concentration raises, the number of positive and negative ions connected with the operation of machining in the zone of machining rises, leading to an increase in the electrochemical erosion. Consequently, with a higher electrochemical etching, less rough surfaces are produced. As IEG decreases, the increases [15]. The optimum IEG value was (0.2 mm) for a superior SR. Also, an elevated SR was determined for a small gap, and the surface finish was reduced with increases in the gap between the tool and the workpiece [26]. One finds a narrower initial gap produces a larger amount of material removal and hence higher surface roughness. Truthfully, the resistance crossways the cathode and anode is proportionate inversely to the original gap. Further electrical energy is spent with no removal of material owing to this resistance. Also, the active electrical field upon the anode is reduced with a broader gap of electrode [25].

In the surface plot of Figure 9a, it can be noticed that the voltage levels 20 V and 30 V, at the allacidic nitrate solution levels, result in a moderate roughness. However, with voltage level 10V, the maximum surface roughness was achieved with the acidic nitrate solution of 80 g/l and 100g/l concentration. While the minimum surface roughness was achieved with an electrolyte concentration of 120 g/l through a voltage of 30 V. Conclusively, the acidic nitrate solution at an 80g/l concentration through an interelectrode gap of 0.2 mm produces higher roughness compared with the concentration of 100 g/l through an interelectrode gap of 0.3 mm.

Empirical modeling

The responses (MRR and SR) to empirical models were also suggested beyond widely debating the parametric influences for the well-defined parameters of output employing Taguchi analysis. The importance of evolved models was determined via Analysis of Variance (ANOVA), which is a usually employed statistical tool [27]. This analysis indicates that the expressed models of response measures are significant, and as per the P-value, the parameters are recognized as significant (P-values < 0.05) at a confidence level of (95%) [28]. As demonstrated by the ANOVA results tabulated in Tables (3, 4, 5, and 6). Adequacy measures (R^2, adjusted R^2, and predicted R^2) found in Tables (4 and 6) depict that the values of these measures are nearer to one for the whole set of responses. This in turn justifies the precision and acceptability of the suggested relations. Also, the evolved empirical models for the two opposing response features, specifically material removal rate and surface roughness are described in Equations 1 and 2,

- Regression equation for MRR:

$$\begin{aligned} MRR &= 0.063489 - 0.00796\ VOLTAGE\ 10 + \\ &+ 0.00026\ VOLTAGE\ 20 + 0.00770\ VOLTAGE\ 30 - \\ &- 0.00641\ EC\ 75 + 0.00464\ EC\ 100 + 0.00177\ EC\ 125 + \\ &+ 0.00568\ IEG\ 0.2 - 0.00059\ IEG\ 0.3 - 0.00509\ IEG\ 0.4 \end{aligned} \tag{1}$$

- Regression equation:

$$\begin{aligned} SR &= 0.30433 + 0.07711\ VOLTAGE\ 10 - \\ &- 0.01878\ VOLTAGE\ 20 - 0.05833\ VOLTAGE\ 30 + \\ &+ 0.03756\ EC\ 75 + 0.00711\ EC\ 100 - 0.04467\ EC\ 125 + \\ &+ 0.02656\ IEG\ 0.2 + 0.01122\ IEG\ 0.3 - 0.03778\ IEG\ 0.4 \end{aligned} \tag{2}$$

Table 3. Analysis of variance for observed MRR

Source	DF	Adj SS	Adj MS	F-Value	P-Value
VOLTAGE	2	0.001104	0.000552	25.94	0.000
EC	2	0.000592	0.000296	13.91	0.000
IEG	2	0.000526	0.000263	12.37	0.000
Error	20	0.000426	0.000021		
Lack-of-Fit	2	0.000325	0.000162	29.04	0.000
Pure Error	18	0.000101	0.000006		
Total	26	0.002648			

Table 4. The model summary for MRR

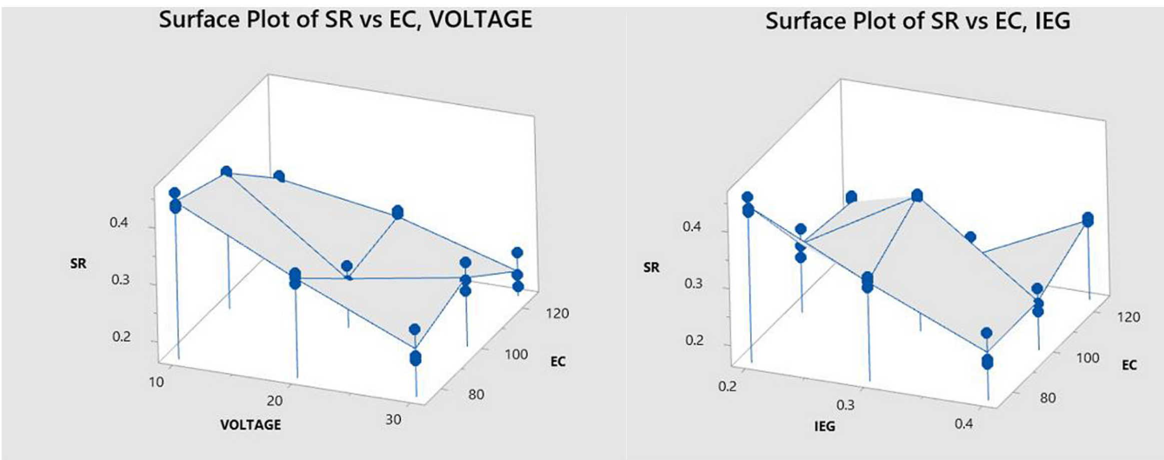
S	R-sq	R-sq(adj)	R-sq(pred)
0.0046129	83.93%	79.11%	70.71%

Table 5. ANOVA for the observed SR

Source	DF	Adj SS	Adj MS	F-Value	P-Value
VOLTAGE	2	0.087314	0.043657	119.30	0.000
EC	2	0.031105	0.015552	42.50	0.000
IEG	2	0.020325	0.010162	27.77	0.000
Error	20	0.007319	0.000366		
Lack-of-Fit	2	0.000488	0.000244	0.64	0.537
Pure Error	18	0.006831	0.000379		
Total	26	0.146062			

Table 6. The model summary for SR

S	R-sq	R-sq(adj)	R-sq(pred)
0.0191297	94.99%	93.49%	90.87%



(a) (b)

Figure 9. Parametric trends for SR with Acidic sodium nitrate concentration: (a) voltage (b) inter electrode gap

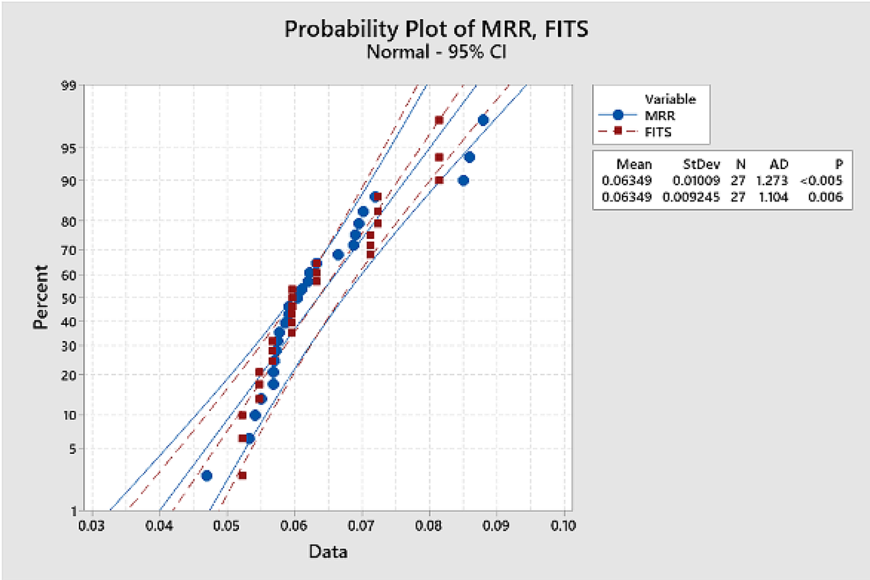


Figure 10. Fitted line plot between predicted and actual values of material removal rate

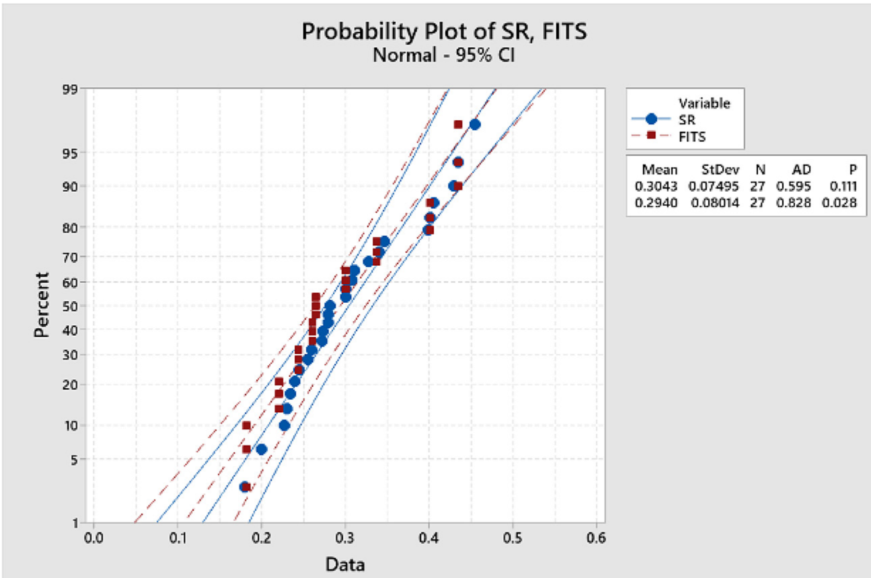


Figure 11. Fitted line plot between predicted and actual values of surface roughness

respectively. In addition, the plot of fitted line for the two output responses (MMR and SR) exhibits the relationship between the predicted results from the regression formulas as well as the real results in the investigational tests, as evidenced in Figures 10 and 11. Furthermore, it proposes that the real values results with the predicted results, which involves the model's reliability and adequacy [29].

CONCLUSIONS

This study presented the possibility of selecting an electrolyte that is environmentally friendly and at the same time has good operability. In this work a mixture of $NaNO_3$ and H_3BO_3 was utilized to produce investigational vision into the stainless steel 316 machining, with considering the significant process factors, voltage, electrolyte concentration, and gap. The influence of these variables on the material removal rate and surface roughness during the electrochemical machining was studied. The following conclusions are extracted:

1. The results manifested that the electrochemical machining of stainless steel 316 with acidic sodium nitrate electrolyte has been effective, and the factors used proved remarkably efficient.
2. An increase in voltage values led to a rise in MRR; the highest MRR has been obtained with voltage 30 V and also gives the better surface finish.
3. The supreme removal of material took place with high electrolyte concentrations. As for surface finish, higher surface finish gained with high level concentrations.
4. The accurate gap in this work for producing elevated removal of material from the workpiece is 0.2 mm, the optimum value. On contrast for surface finish, top-notch surface roughness attained with lower gap value.
5. Higher MRR (0.0823) was found with a voltage of 30 V, an electrolyte concentration of 100, and a gap of 0.2 mm.
6. The lowest SR (0.1881 μm) with a voltage of 30 V, an electrolyte concentration of 125, and a gap of 0.3 mm.
7. From ANOVA analysis, it was noted that every separate factor possesses significance upon the output response.
8. The fitted line plots confirmed that the real results are in agreement with the predicted results, which involves the model's reliability and adequacy.

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