5th International Conference on Engineering and Applied Natural Sciences

August 25-26, 2024 : Konya, Turkey

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ANOVA and Multiple Regression Analysis of Electropolishing Parameters for SLM 316L Stainless Steel

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Abstract – Electropolishing is an electrochemical surface treatment process that improves the appearance, smoothness and corrosion resistance of metal surfaces by selectively removing the material from the surface. This study focuses on the analysis of the electropolishing process of selective laser-melted (SLM) 316L stainless steel, which is widely used in marine, biomedical and chemical industries because of its superior corrosion resistance in harsh environments. This research investigates the effects of key process parameters (voltage, time and temperature) on surface roughness and polished depth. A full factorial experimental design was used to analyze the effects of these parameters, which were analyzed using Analysis of Variance (ANOVA) and multiple regression analysis. The findings revealed that voltage was the most effective factor, significantly affecting surface roughness by 67% and polished depth by 37.33%, both statistically significant ($p < 0.05$). Temperature also plays an important role in polished depth, contributing 33.52%, whereas its effect on surface roughness is minimal and not significant. The time parameter had a negligible effect on surface roughness (0.14%) and a moderate effect on polished depth (6.75%); none of the effects were statistically significant. In addition, multiple regression analyses produced equations with high r-squared values. The results highlight the importance of optimizing these parameters to improve the surface quality and functional performance of 316L stainless steel components, especially in applications where surface quality is critical.

Keywords – Electropolishing, ANOVA, Roughness, Polished depth, Multiple regression

I. INTRODUCTION

Electrochemical polishing , also known as electropolishing, is an electrolytic anodic dissolution method based on the regulation of the removal of materials that reduce roughness and make the workpiece appear bright and smooth [1]. Electropolishing involves the electrochemical treatment of metals and alloys to produce surfaces with extremely low surface roughness [2], no residual surface tension or grooves [3, 4] and improved corrosion resistance of stainless steel [5–7]. A number of variables, including the current density, electropolishing duration, electrolyte temperature and concentration, electrode gap, distance between electrodes, starting surface quality, workpiece, and electrode material, affect the electropolishing process performance [8]. Electropolishing is a surface treatment technique for 316L stainless steel that produces a damage-free surface using anodic dissolution to remove defective layers left over by previous mechanical treatments [9]. It also creates a new passive oxide layer that improves corrosion resistance [10].

316L stainless steel is widely used in marine, biomedical equipment, chemical and petrochemical industries because of its superior corrosion resistance in highly corrosive conditions, including salt water, acidic and alkaline environments [11]. Due to poor machining, the surface of 316 L stainless steel is highly contaminated and has a rough texture. This can result in fatigue crack welding, large tolerances and even

higher friction [12, 13]. Consequently, to avoid these problems in industrial production, the post-polishing technique is an important step [14].

ANOVA is an important method used by different disciplines to measure the effects of various parameters. Wamg et al. [15] used ANOVA and gray relational analysis to optimize the electrochemical processing parameters of 2Cr13 stainless steel. In another study [16], a hybrid method known as EC2A2FM was created and evaluated to enhance the surface finish of metallic components by combining electrochemical machining with abrasive flow machining. ANOVA was used to identify the most efficient process parameters, and the Taguchi method was used to carry out the experimental design. ANOVA showed that certain parameters significantly affected the amount of material

In this study, ANOVA analysis of the electropolishing process of selective laser-melted (SLM) 316L stainless steel samples was carried out. The effects of electropolishing parameters such as voltage, time, and temperature on the roughness and electropolishing depth were investigated. In addition, multiple regression analysis was performed. The results of ANOVA clearly demonstrate the effectiveness level and statistical significance of the parameters.

II. Materials and Methods

In this study, statistical analysis was conducted on stainless-steel 316L SLM samples that were electropolish using various parameters, including voltage, time, and temperature. The selective laser remelting process was previously reported by Ref. [17]. Based on the results obtained in Ref. [17], an electropolishing process was performed in Ref. [18] on remelted SLM stainless steel 316L parts. The selected parameters: voltage (4V, 6V, 8V), time (30, 45, 60 min) and temperature (20°C, 40°C, 60°C) were tested in a full factorial design to evaluate their effects on surface roughness and material removal depth, as shown in Table 1. The experiments were carried out in a controlled setup using Ethaline containing 5% oxalic acid as the electrolyte, and the results were calculated by averaging three replicates for each condition. In this study, experimental data were taken directly from Ref. [18], and statistical analysis procedures were applied to these data. The experimental processing details are described in Refs. [17, 18].

Table 1. Process parameters and experimental design levels.

	Levels		
Factors	1	2	3
Volt (V)	8	6	4
Time (min)	60	45	30
Temperature (°C)	60	40	20

III. Results and Discussion

Analysis of variance is a statistical approach that investigates whether there is a difference between the means of two different groups using variance. Although there are different methods used to compare two groups (Z or T test), the most common is the F test, i.e. ANOVA. When the level of importance of more than two groups is to be evaluated, the difference between them can only be determined by ANOVA [19]. The ANOVA results showing the effect of the electropolishing parameters (volt, time, and temperature) on the roughness of the electropolish surface is given in Table 2. Volt has a 67% effect on the response variable and this effect is statistically significant because the P value is less than 0.05. Time has an effect of 0.14% on the response variable; this effect is negligible and the P value is 0.948; thus, it is not statistically significant. Temperature had an effect of 7.56%, but this result was not statistically significant because the

p value was higher than 0.05. The findings of this study reveal that voltage is the most critical factor and that the effect of other factors is limited.

Table 2. ANOVA for Surface Roughness of Electropolished SLM Stainless Steel 316L

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Volt (V)	2	0.476551	67.00%	0.476551	0.238276	26.48	0.000
Time (min)	2	0.000968	0.14%	0.000968	0.000484	0.05	0.948
Temperature (°C)	2	0.053781	7.56%	0.053781	0.026890	2.99	0.073
Error	20	0.179990	25.30%	0.179990	0.009000		
Total	26	0.711290	100.00%				

Table 3 displays the ANOVA results, which illustrate how the electropolishing parameters of volt, time, and temperature affect the polished depth of the electropolish surface. According to the results, the voltage factor had the largest effect on the outcome variable 37.33%. p-value is less than 0.05, which indicates that voltage has a highly statistically significant effect on the response variable. The temperature factor also has a significant effect; it explains 33.52% of the total variance and the p-value of less than 0.05 indicates that temperature has a strong effect on the response variable. The time factor has a lower effect with a contribution of 6.75%. The p-value of 0.072 indicates that the effect of this factor is borderline and may not be considered statistically significant. While time has a minor and insignificant effect, voltage and temperature appear to have a considerable impact on response variable .

Table 3. ANOVA for Polished Depth of Electropolished SLM Stainless Steel 316L

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Volt (V)	2	4175.9	37.33%	4175.9	2087.9	16.67	0.000
Time (min)	2	755.3	6.75%	755.3	377.6	3.01	0.072
Temperature (°C)	2	3750.4	33.52%	3750.4	1875.2	14.97	0.000
Error	20	2505.6	22.40%	2505.6	125.3		
Total	26	11187.1	100.00%				

Multiple regression analysis was performed using Minitab. The regression equation for roughness is given in equation 1. In the equations X1 is Volt (V), X2 is time (min) and X3 is temperature (°C). The R-squared value was determined as 0.9258. The R-squared value was greater than 0.9, indicating that the regression equation is reliable.

$$\text{Roughness} = 1.676 - 0.4352\ X1 - 0.01289\ X3 + 0.03357\ X1^{\wedge}2 + 0.002598\ X1*X3 \quad (1)$$

The multiple regression equation for the polished depth value is given in equation 2. As a result of the analysis, the R^2 value was calculated as 0.9570. In other words, the regression equation has a confidence of 95.7%

$$\text{Polished Depth} = 116.7 - 28.54\ X1 - 1.198\ X2 - 1.632\ X3 + 1.404\ X1\text{^}2 + 0.1742\ X1*X2 + 0.2823\ X1*X3 + 0.01456\ X2*X3 \quad (2)$$

IV. CONCLUSION

In this study, the effects of various parameters, such as voltage, time, and temperature, on the roughness and polishing depth of the surfaces of 316L stainless-steel samples produced by the SLM method were investigated. As a result of the study, the following conclusions were obtained ;

- The voltage factor had the greatest effect on the surface roughness (67%) and was statistically significant.
- The effects of time and temperature on roughness is very low and not statistically significant.
- In terms of polishing depth, both the voltage and temperature factors had significant effects; the voltage contributed 37.33% and the temperature contributed 33.52%. The effects of both factors were statistically significant.
- The effect of time was lower (6.75%) and not statistically significant.

The overall findings of this study reveal that optimizing the voltage and temperature parameters during electropolishing is critical for achieving the desired surface properties.

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