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Parameters Optimization for Electropolishing Titanium by Using Taguchi-Based Pareto ANOVA

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Abstract: Material removal rate in electropolishing is often overlooked because this process generally addressed for surface finish; however, it is paramount on metallic sheet machining possessed with intricate geometry. Electropolishing removes metallic material from the surface of a workpiece based on anodic dissolution process. The material removal rate depends on the current density, electrolyte, the strength of the magnetic field, polishing time and temperature. In this study, three factors of applied voltage, electrolyte composition and magnetic field were evaluated using Taguchi approach to improve the material removal rate in the electropolishing of a pure titanium (99.5%) workpiece. The experiments were undertaken as per Taguchi L_9 (3^3) orthogonal array, and further analyzed using Pareto ANOVA to determine the most significant parameter. It was found that the optimum parametric combination to maximize the material removal rate were, applied voltage of 15 V, ethanol concentration of 20 vol.% and magnetic field of 0.51 T. The experimental results show that the responses in electropolishing process can be improved through this approach.

Keywords: electropolishing; Taguchi; titanium; SS 304; material removal rate; environmentally sound technologies

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1. Introduction

Titanium has a wide variety of industrial uses in aerospace, medical implants, chemical processing, automotive, marine, and power generation, due to their high strength-to-weight ratio, corrosion resistance and durability. The low density and excellent physical properties (high yield strength and modulus of elasticity) make it suitable for use in high-temperature service environments including in petroleum and chemical industries [1,2]. Its biocompatible property is also ideal in medical applications such as in orthopedic bone implants and as hard tissue replacements in artificial joints and dental implants [3,4]. However, titanium is identified as a difficult-to-machine material, requiring relatively large cutting forces, yielding further in high cutting temperatures during the manufacturing process [5–10].

For most applications, the machined titanium components usually undergo surface finishing to produce the final high-quality surface, either by mechanical or chemical polishing [11–15]. Mechanical polishing is generally used to smoothen the surfaces of titanium; however, it may induce surface residual stress, scratches, cracks, and plastic deformation [16]. Furthermore, despite water cooling and slow-speed abrading, mechanical polishing can sometime result in the adhesion of the abrasive particles on the polished surface, changing the chemical bond state and contaminate the titanium surface by the abrasive polisher [17]. This contamination is negatively affecting its biocompatibility and corrosion resistance.

Some applications of titanium components such as microchannel on dialysis instrument and bone implants are intricate, highly accurate and have complex geometry, thus require extended processing time to produce the final shape by conventional polishing. At times, the conventional polishing is even not feasible due to the shape intricacy and thickness of the components. Thus, non-conventional polishing methods such as chemical and electrochemical processes are preferred for polishing titanium without the use of abrasives [18–20]. However, the main issue with chemical polishing is the handling and safety requirements during the process as well as related environmental concerns, how to dispose the used chemicals along with the generated gas [21,22]. Therefore, an efficient yet environmentally friendly polishing process such as electropolishing can be used as an alternative to improve the quality of the material surface [23–26].

In principle, material removal by electropolishing involves the electrochemical dissolution of the workpiece surface. Electrolysis uses the principles of Faraday's Law which determine that electropolishing possesses is quite different technique than the conventional finishing method, including grinding, milling, grinding, milling and buffing as the final touch, due to that electropolishing is a considered as a non-contact machining that damage free process. The polishing phenomenon is portrayed by the removal of roughness, the absence of crystallographic and grain-boundary strike, and generate the production of bright and smooth surfaces [27]. The workpiece to be polished is positioned as the anode and is then connected to the positive electrode of a DC power supply. As the current flow, the surface of the anode (workpiece) in contact with the electrolyte is oxidized into metal ions, resulting in the material removal from the surface. In electropolishing process, a combination of chemical reaction, fluid mechanics, electric field as well as material properties comprise a significant number of independent machining parameters which are quite difficult tough to study in determine a very comprehensive conclusion. Therefore, Lu et al. [28] introduced a new approach using the deep CNN with Bayesian optimization to improve the accuracy of the prediction and rate of convergence for the electrochemical machining drilling process. The proposed model has provided fewer training iterations to converge and fewer prediction errors compared to the previous prediction method. Deng et al. [29] revealed that regardless of composition of the electrolyte, pulse duty cycle, current density and other polishing parameters, an isotropic etching under mass transfer polarization plays an important role for having smooth surface via electropolishing. In addition, the etching isotropy probably a more efficient and direct for the process development of practical application of electropolishing to different type of metals or alloys. Karim et al. [30] reported a simple, rapid and efficient of titanium electropolishing by utilizing an environmentally friendly choline chloride-based ionic liquid, known as Ethaline. Under machining condition of 6–10 V in 30 min of machining time, a potential electropolishing process was performed without the obvious presence of gas evolution. In addition, by carrying out the current procedure, the microscopic results showed leveling and brightening of the titanium surface which is the responsibility of the current procedure.

Due to that electropolishing process produces a smooth, damage free surface that improves the adhesion properties, it is often used to create surfaces for processes such as coating that promote good wetting of the surface material and to facilitate retention of a liquid on the metallic surface [31]. Gram et al., [32] evaluated whether the smoother surface roughness, Ra 0.01 um compared to Ra 0.9 has provided hygienic characteristics of stainless steel used in medical and food processing industry. *Pseudomonas* sp., *Listeria monocytogenes* and *Candida lipolytica* were used to study the adhesion of microorganisms on the metallic surface. The study revealed that the surface finish has no effect in bacterial adhesion, however, it is more essential parameter for the property of corrosion resistance of the surface. Chen et al. [33] investigated electropolishing of Ti60 to determine the influences of several processing parameters on the surface roughness. It was found that the frequency of the pulsed power supply is the most important parameters to significantly decrease the surface roughness of the workpiece Guo et al. [34] proposed optimal conditions for fabricating nanostructures on titanium implants with curved geometry. Short-time anodization on implants were performed to understand the nanostructure self-ordering. It was found that decreasing the anodization voltage minimizes excessive TiO_2 dissolution as well as improving the efficiency of nanopores fabrication on titanium wires. Sathish et al. [35] optimized the machining parameters by evaluating the effect of duty ratio parameters such as material removal rate, machining time and overcut in a micro electrochemical drilling process. It was found that the material removal rate increases with the increases of the duty cycle value. Using an aqueous electrolyte as the electropolishing media, Ferchow et al. [36] have found a significant improvement on the external surface roughness of a complex selective laser melting metal part. Thus, the electrolyte concentration, the electrolyte flow rate and the applied voltage are significant factors that can influence the material removal rate [37–39].

Incorporation of a magnetic field into the electropolishing process in a process known as magneto-electropolishing (MEP) further improves the surface quality of stainless steel by speeding up the rate of dissolution [40]. Other study reveals that the application of magnetic force on titanium altered the Young's modulus value, hence offer better performance [41]. The MEP process utilizes an external magnetic force generated from either a permanent neodymium magnet or an electromagnet to assist dissolution process of the material over the polished surface. The characteristic of self-contained electrolyte whirling introduced by the magnetic force has lowered the oxygen content in the top layers of titanium [42], and control the Cr:Fe ratio at the surface of austenitic stainless steel, which is advantageous to the microhardness [43]. MEP also improve corrosion resistance of Co-Cr alloy, one of biomaterials mostly used as implants and cardiovascular stent [44]. However, the relationship between electropolishing parameters, such as the current density and the electrolyte composition are yet to be investigated in detail. The optimization of material removal rate in electropolishing is often left out because most works were focused on acquiring the finest surface finish for each combination of workpiece-electrolyte used. Albeit the fact, material removal rate is undoubtedly one important machining factors when it comes to machining flat sheet metallic components, particularly when manufacturing microparts with intricate geometry [26]. Electropolishing with high material removal rate is a highly viable method for manufacturing meso- to microparts rapidly, with high accuracy and at exceptionally low cost.

That being the case, the present study aims to optimize the main electropolishing parameters to obtain higher material removal rate by considering the influence of applied voltage, concentration of ethanol in electrolyte and the use of magnetic field by using Taguchi analysis. A high removal rate is targeted to be comparable to mechanical polishing methods. In this paper, Pareto ANOVA technique was used to analyze the effect of three machining parameters and its level in achieving high material removal rate. The structure of this paper presents Section 1 describing recent approaches to improve the material removal mechanism as well as surface quality in electropolishing process. Section 2 deals with the details of materials, experimental methods and statistical analysis used in this study. Section 3 focuses on the experiment results related to the effect of machining parameter on material removal rate based on the statistical analysis result.

2. Materials and Methods

2.1. Material and Solution

Commercially-pure Grade 1 titanium (99.5%) and stainless steel 304 (SS 304) sheets (Nilaco Corp., Tokyo, Japan) measuring 20 mm × 10 mm and 200 µm in thickness were used as the anode (workpiece) and cathode (tool electrode), respectively. Tables 1 and 2 present the mechanical properties and chemical composition of pure titanium. Tables 3 and 4 present the mechanical properties and chemical composition of SS 304. Meanwhile, the 1M electrolyte solution with various concentrations, i.e., 0, 10 and 20 vol.%, was prepared from NaCl powder (Merck & Co., Inc., Rahway, NJ, USA) dissolved in Ethylene glycol (Merck &

Co., Inc., Rahway, NJ, USA). A digital microscope, Dino-lite AM4515T8 (AnMo electronics, New Taipei City, Taiwan) with resolution of 1.3 MP and a magnification rate of 700×~900× was used to capture the image of the electropolished of titanium surface.

Table 1. Mechanical properties of pure titanium (JIS H 4600 TR270C).

Yield Strength	Elongation	Tensile Strength
218 MPa	45%	320 MPa

Table 2. Chemical composition of pure titanium in wt.% (JIS H 4600 TR270C).

N	C	H	Fe	O	Ti
0.00	0.00	0.02	0.03	0.04	Bal.

Table 3. Mechanical properties of SS 304 (JIS G4313).

Hardness	Tensile Strength	Elongation
378 HV	1202 MPa	6%

Table 4. Chemical compositions of SS 304 in wt.% (JIS G4313).

C	Cr	Mn	Si	P	S	Ni
0.04	18.21	0.91	0.53	0.030	0.002	8.09

Figure 1 illustrates the schematic of the experimental set-up. The distance between the workpiece and tool electrode was maintained at 20 mm. The constant experimental parameters are summarized in Table 5. The selection of the experimental parameters as presented in Table 5 was based on the preliminary experiment result and previous research [45]. Each experiment was conducted for 50 min, and the final weight of the anode was measured using a digital weight balance (Fujitsu FS AR 210, readability: 0.1 mg) to determine the material removal rate.

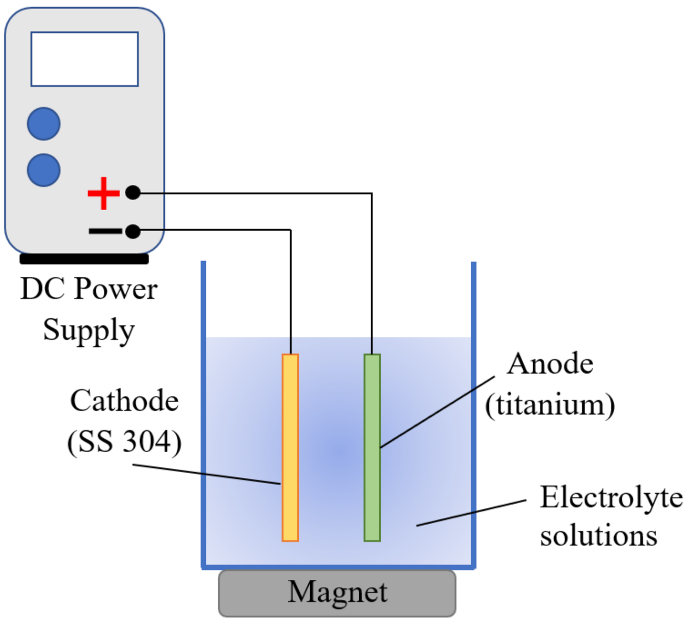


Figure 1. Experimental setup of electropolishing.

Table 5. The experimental parameters applied in this research.

Anode	Pure titanium sheet (99.5%) 20 mm × 10 mm × 0.2 mm
Cathode	Stainless steel 304
Polishing time	50 min
Electrolyte solutions	1.0 M NaCl, 99.0% ethylene glycol

2.2. Taguchi Analysis

The Taguchi method is one of the best experimental technologies that provide much-reduced variance for experiments to be performed within the permissible limit of factors and levels. It identifies the significant level of a factor which affects the specific performance parameter. In this study, three parameters of (1) applied voltage, (2) ethanol concentration and (3) magnetic field were selected to be optimized for material removal rate of the titanium workpiece. In general, optimization using Taguchi can be categorized into the criteria of larger-the-better, nominal-the-best type, or the- smaller-the-better. In the Taguchi method, the term 'signal' represents the desirable value of the output (mean) and the term 'noise' means the undesirable value of the output, which is the standard deviation. A signal-to-noise-ratio (*S/N* ratio), which is a measure of robustness to identify the control factor that minimize the effect of noise, can then be used as an objective function to determine the best process parameters. In this study, the larger-the-better type criteria is selected because maximum material removal rate is desirable, thus maximizing the *S/N* ratio defined by Equation (1).

The *S/N* for the larger-better ratio is calculated using the following equations [46]:

$$S/N_S = -10\, log_{10}\left[\frac{1}{n}\left(\sum_{i=1}^{n}\frac{1}{y_i^2}\right)\right] \tag{1}$$

where y_i is the observations of quality characteristic under different noises and n is the number of the experiments in the factor level combination performed.

The material removal rate is calculated by using Equation (2):

$$Material\ removal\ rate = \frac{W_b - W_a\ (\mathrm{mg})}{Machining\ time(\mathrm{min})} \tag{2}$$

where W_b is the weight of the workpiece before electropolishing and W_a is the weight of the workpiece after the electropolishing process.

2.3. Configuration of Experiment Factors and Their Levels

Table 6 presents the factors and levels of the electropolishing machining parameters. The three control factors; the applied voltage, ethanol concentration and magnetic field, were designated as factor *A*, *B* and *C*, respectively. The three levels chosen for each factor, namely 0 V, 10 V and 15 V (applied voltage), 0 vol.%, 10 vol.% and 20 vol.% (ethanol concentration) and 0 T, 0.41 T and 0.51 T (magnetic field). An L_9 orthogonal array was selected for the design of experiments, as configured in Table 7. Triplications were conducted for each set of experiment to ensure reproducibility and accuracy of the results.

Table 6. Factors and levels of the EP machining parameters.

Control Factor		Levels		
		1	**2**	**3**
A	Applied Voltage (V)	5	10	15
B	Ethanol concentration (vol.%)	0	10	20
C	Magnetic field (T)	0	0.41	0.51

Table 7. Configuration of EP machining parameters.

Exp. No	Configuration of Machining Parameters			Material Removal Rate (R_a)
	A	B	C	
1	$A1$	$B1$	$C1$	MRR_{a1}
2	$A1$	$B2$	$C2$	MRR_{a2}
3	$A1$	$B3$	$C3$	MRR_{a3}
4	$A2$	$B1$	$C2$	MRR_{a4}
5	$A2$	$B2$	$C3$	MRR_{a5}
6	$A2$	$B3$	$C1$	MRR_{a6}
7	$A3$	$B1$	$C3$	MRR_{a7}
8	$A3$	$B2$	$C1$	MRR_{a8}
9	$A3$	$B3$	$C2$	MRR_{a9}

2.4. Pareto ANOVA

Pareto analysis of variance (ANOVA) was also used to identify the factors that have the greatest impact on a particular response variable by comparing variances across the means of the three groups. Subsequently, the pareto optimal point, which is the set of factor levels that maximizes the response variable, can be identified. This means that the electropolishing parameters obtained from the pareto-optimal are the combination that contribute to achieve high removal rate. In the next section, Pareto ANOVA analysis is implemented to study the interactions of selected input parameters in the Taguchi method.

3. Results and Discussion

Table 8 summarizes the measured material removal rate and the calculated S/N ratio for each set of experiment in the L_9 array. Figure 2 shows the visual quality of the surface machined using 9 different machining combinations of EP process. The average S/N ratio level for each factor, as shown in Table 9, can be obtained from the numerical values listed in Table 7. The average S/N ratio for each level and the separate effects of each factor, commonly called as the main effects, are shown in Figure 3.

The average S/N ratio of the levels (1, 2 and 3) for each factor (A, B and C), as shown in Table 9 and Figure 3, are obtained using the following calculations:

- Average S/N ratio $\overline{A1}$:

$$\overline{A1} = \frac{\sum A1}{3} = \frac{(16.2 + 32.9 + 45.5)}{3} = 31.5$$

- Average S/N ratio $\overline{A2}$:

$$\overline{A2} = \frac{\sum A2}{3} = \frac{(50.8 + 54.4 + 54.5)}{3} = 53.17$$

- Average S/N ratio $\overline{A3}$:

$$\overline{A3} = \frac{\sum A3}{3} = \frac{(51.8 + 56.7 + 60.6)}{3} = 56.37$$

- Average S/N ratio $\overline{B1}$:

$$\overline{B1} = \frac{\sum B1}{3} = \frac{(16.2 + 50.8 + 51.8)}{3} = 39.59$$

- Average S/N ratio $\overline{B2}$:

$$\overline{B2} = \frac{\sum B2}{3} = \frac{(32.9 + 54.4 + 56.7)}{3} = 47.99$$

- Average S/N ratio $\overline{B3}$:

$$\overline{B3} = \frac{\sum B3}{3} = \frac{(45.5 + 54.4 + 60.6)}{3} = 53.51$$

- Average S/N ratio $\overline{C1}$:

$$\overline{C1} = \frac{\sum C1}{3} = \frac{(16.2 + 54.4 + 56.7)}{3} = 42.39$$

- Average S/N ratio $\overline{C2}$:

$$\overline{C2} = \frac{\sum C2}{3} = \frac{(32.9 + 50.8 + 60.6)}{3} = 48.12$$

- Average S/N ratio $\overline{C3}$:

$$\overline{C3} = \frac{\sum C3}{3} = \frac{(45.5 + 54.4 + 51.8)}{3} = 50.58$$

Table 8. Material removal rate and *S/N* ratio.

Exp. No	**Control Factor**			**Material Removal Rate (mg/min)**			**Mean**	***S/N* Ratio (dB)**
				Noise Factor				
	A	***B***	***C***	**N0**	**N1**	**N2**		
1	*A*1	*B*1	*C*1	18	12	4	11.3	16.2
2	*A*1	*B*2	*C*2	166	34	40	80	32.9
3	*A*1	*B*3	*C*3	148	288	196	210.7	45.5
4	*A*2	*B*1	*C*2	362	344	334	346.7	50.8
5	*A*2	*B*2	*C*3	482	722	460	554.7	54.4
6	*A*2	*B*3	*C*1	638	432	560	543.3	54.4
7	*A*3	*B*1	*C*3	308	410	560	426.0	51.8
8	*A*3	*B*2	*C*1	1482	598	556	878.7	56.7
9	*A*3	*B*3	*C*2	1062	970	1250	1094	60.6

Table 9. Average *S/N* ratio by factor levels (dB).

	Factor		
	A	***B***	***C***
Level 1	31.55	39.59	42.39
Level 2	53.17	47.99	48.12
Level 3	56.37	53.51	50.58
Max-Min	24.83	13.92	8.19
Average	47.03	47.03	47.03

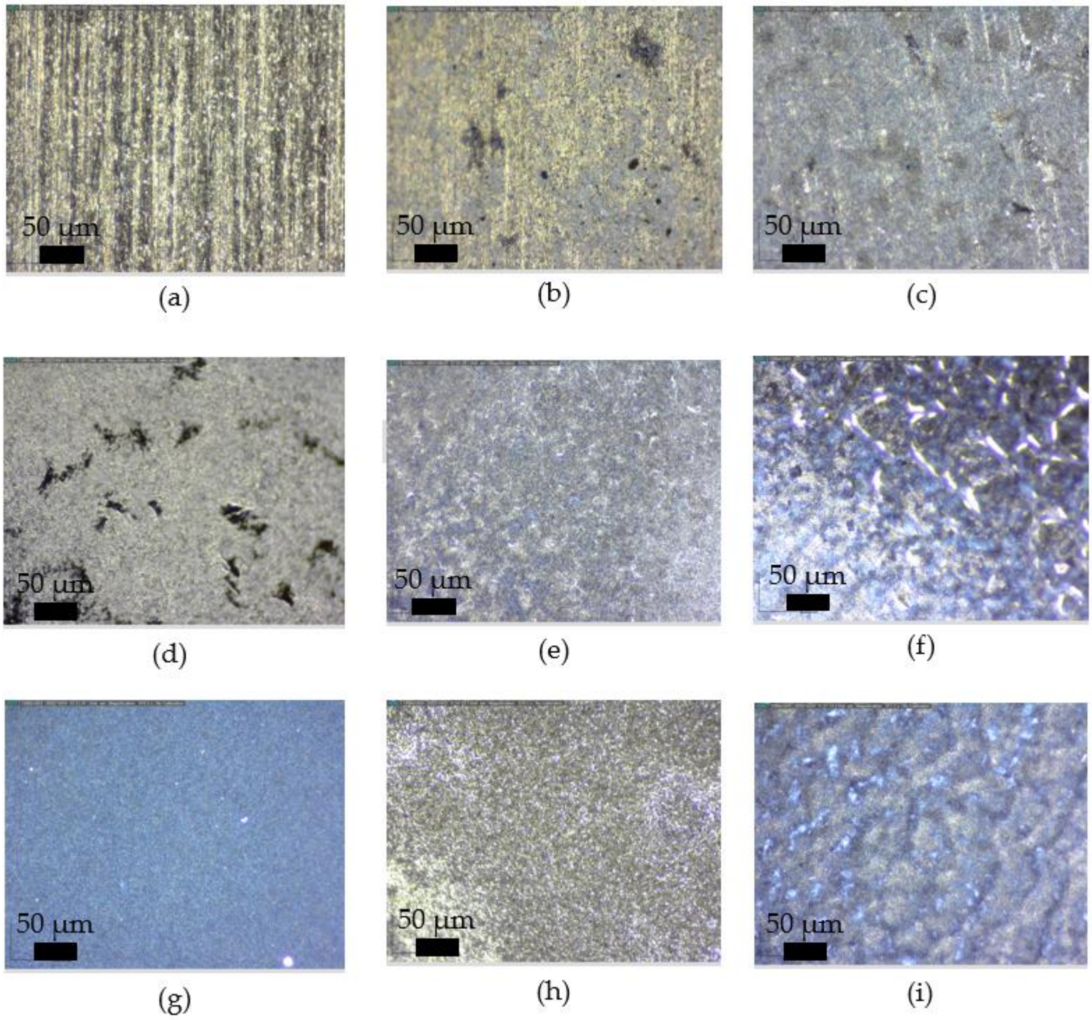


Figure 2. The morphologies of the titanium surface machined at different electropolishing parameters (**a**) 5 V, 0 vol.%, 0 T; (**b**) 5 V, 10 vol.%, 0.41 T; (**c**) 5 V, 20 vol.%, 0.51 T; (**d**) 10 V, 0 vol.%, 0.41 T; (**e**) 10 V, 10 vol.%, 0.51 T; (**f**) 10 V, 20 vol.%, 0 T (**g**) 15 V, 0 vol.%, 0.51 T; (**h**) 15 V, 10 vol.%, 0 T; (**i**) 15 V, 20 vol.%, 0.41 T.

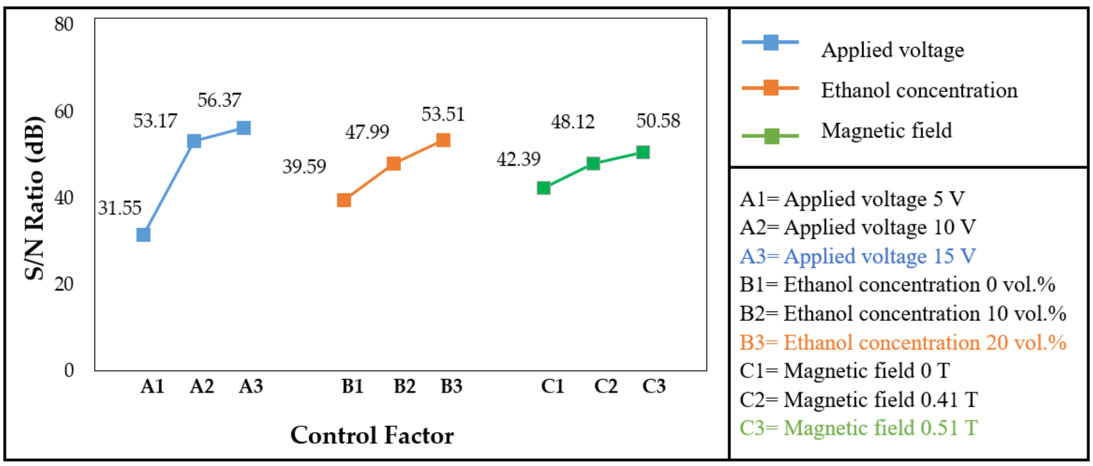


Figure 3. Plot of control factor effect.

3.1. Combination of Optimal Level for Each Factor and Verification Test

The optimal level for high material removal rate can be determined by the level with the highest *S/N* ratio value. From Figure 3 and Table 10, the optimum combination for high material removal rate is $A3B3C3$. This means the optimal levels to yield high material removal rate are applied voltage of 20 V ($A3$), ethanol concentration of 20 vol.% ($B3$) and magnetic field of 0.51 T ($C3$).

Pareto ANOVA analysis has been employed to study the contribution of selected optimized parameters on obtaining high material removal rate. Figure 4 shows the Pareto ANOVA analysis on material removal rate. The significant factors are selected starting from the left-hand side of diagram and the summation value should surpass 90%. Since the sum of the first factor (applied voltage) and second factor (ethanol concentration) was 92.91%, thus indicate that the factor of magnetic field is not significant to aim for high material removal rate. To summarize, to achieve high material removal rate, the parameters selected should be the applied voltage of 15 V and 20% of ethanol concentration.

The sum of factors A, B, and C for level 1, 2 and 3, as presented in Table 11, can be calculated as follow:

$$\text{Sum of factor level } A1 = 16.2 + 32.9 + 45.5 = 94.64$$

$$\text{Sum of factor level } A2 = 50.8 + 54.4 + 54.5 = 159.52$$

$$\text{Sum of factor level } A3 = 51.8 + 56.7 + 60.6 = 169.12$$

$$\text{Sum of factor level } B1 = 16.2 + 50.8 + 51.8 = 118.78$$

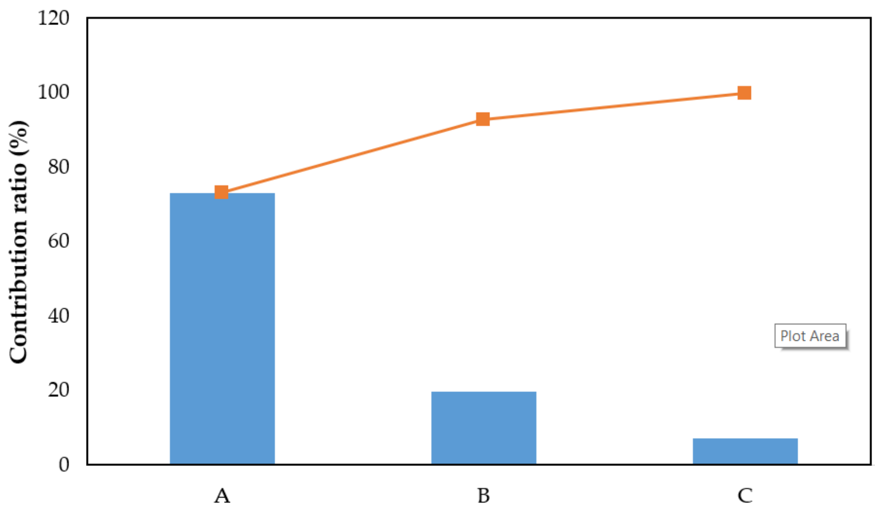
$$\text{Sum of factor level } B2 = 32.9 + 54.4 + 56.7 = 143.96$$

$$\text{Sum of factor level } B3 = 45.5 + 54.4 + 60.6 = 160.54$$

$$\text{Sum of factor level } C1 = 16.2 + 54.4 + 56.7 = 127.17$$

$$\text{Sum of factor level } C2 = 32.9 + 50.8 + 60.6 = 144.36$$

$$\text{Sum of factor level } C3 = 45.5 + 54.4 + 51.8 = 151.75$$



Contribution ratio (%)	A	B	C
Factor	73.2	19.71	7.09
Percent	73.2	19.71	7.09
Cumulative (%)	73.2	92.91	100

Figure 4. Pareto ANOVA analysis of optimum electropolishing parameter on material removal rate.

Table 10. Optimal condition for EP process.

Factor	Level
A. Applied voltage	15 Volt
B. Ethanol concentration	20 vol.%
C. Magnetic field	0.51 T

Table 11. Calculation of the contribution ratio of electropolishing machining parameters.

Factor		*A*	*B*	*C*	Total
Sum of factor level	1	94.64	118.78	127.17	1269.84
	2	159.52	143.96	144.36	
	3	169.12	160.54	151.75	
Square of difference (δ)		4208.74	1926.38	769.74	6904.86
Degrees of Freedom ($\varnothing$)		2	2	2	
$\delta/\varnothing$		4924.034	1326.18	477.02	6727.24
Contribution ratio (%)		73.2	19.71	7.09	100
Optimum combination of significant factor levels		*A3-B3-C3*			
		The optimal level of each significant factor is the level which maximizes the sum of *S/N* ratios			
Remarks on optimum combinations		The significant factors are chosen from the left-hand-side in the above Pareto diagram which cumulatively contribute about 90%			

3.2. Effect of Applied Voltage on Material Removal Rate

The significant factors in pareto ANOVA analysis are chosen from the left-hand side which cumulatively contribute about 90%. Based on Pareto analysis of Figure 4, the applied voltage emerged as an important parameter in electropolishing process and shown to be the most significant parameter (73.2% significance) in obtaining high material removal.

In electropolishing process, there is a relationship between current density of the applied voltage with the increase of the anode dissolution process [47]. This relationship is known as a polarization curve, which is obtainable when the tool and the workpiece are placed close together and the applied current is increased [27,48]. In region I (etching), the current density increases with applied voltage, hence the workpiece is directly dissolved. However, in region II (passivating), the current density declines due to the formation of diffusion layer, a passive oxide layer on the anodic surface. In Region III (polishing), known as the plateau region, where the electropolishing occurs, there is barely any increase of current density as the applied voltage increases. The diffusion layer that limits the current density in region II and III breaks down, then dissolves in region IV (pitting), and as a consequence, increases the current density with the increase in voltage. This effect causes rapid anodic dissolution [39] and as a result, it would produce higher material removal rate [27,44]. As the applied voltage contributes to 73.2% of significance level, the statistical approach verified the density-voltage relationship to obtain high removal rate.

3.3. Effect of Ethanol Concentration on Material Removal Rate

In order to ensure human and environmental safety, this work uses ionic liquids as electrolytes, which is the mixture of ethylene glycol and salt, instead of acidic solutions [11]. To improve the electrical conductivity of the electrolyte solution, organic and inorganic additives are added to the solution [10]. In this work, ethanol was used as the additive and the concentration was made as one of the factors to observe its effect in increasing material removal.

The pareto ANOVA analysis in Figure 4 shows that the concentration of ethanol in the electrolyte solution (ethylene glycol-NaCl) has a significant factor of 19.17% to material removal rate. This factor is considered as one of significant parameters in material removal since it is cumulatively exceeded 90% value after the applied voltage. During the electropolishing process of pure titanium, Ti^{4+} ions reacts with the Cl^- ions from the electrolyte to form titanium tetrachloride ($TiCl_4$), as shown in Equation (3) [42]:

$$Ti^{4+} + 4Cl \rightarrow TiCl_4 \quad (3)$$

$TiCl_4$ is a viscous yellow liquid that could retard the dissolution rate of the polished material. The ethylene glycol used as the electrolyte always contains small amount of water (H_2O), and with the absence of ethanol, the reaction shown in Equation (4) [42] can take place. The reaction of $TiCl_4$ with H_2O will generate TiO_2 and adhere onto the surface of the titanium sheet, as illustrated in Figure 5 (ethanol 0 vol.%).

$$TiCl_4 + 2H_2O \rightarrow TiO_2 + 4H^{4+} + 4Cl^- \quad (4)$$

However, in the presence of ethanol into the electrolyte solution, the viscous layer, $TiCl_4$ reacts with H_2O through the ethanol, hence the reaction in Equations (4) and (5) [42] occur:

$$TiCl_4 + EtOH \rightarrow Ti(OEt)_4 + 4H^{4+} + 4Cl^- \quad (5)$$

$$Ti(OEt)_4 + 2H_2O \rightarrow Ti_2 + 4HOEt \quad (6)$$

where Et is ethanol presence in the electrolyte solution.

Thus, the added ethanol reduces the thickness of the $TiCl_4$ layer, due to its solubility and viscosity to establish the appropriate thickness of the $TiCl_4$, as shown in Figure 5 (ethanol 20 vol.%), hence improving material removal rate.

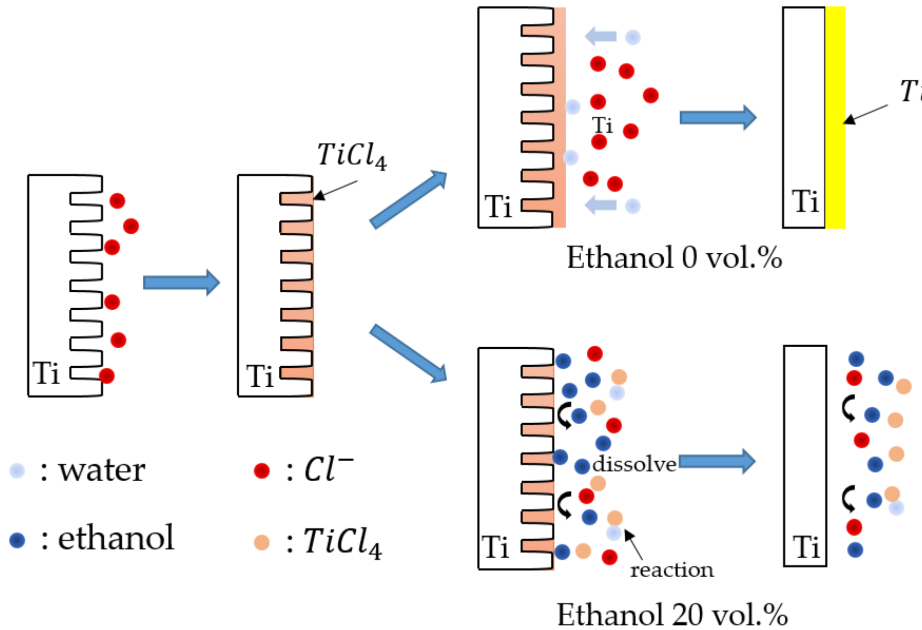


Figure 5. Illustration of the electropolishing mechanism of titanium according to the ethanol concentration in electrolyte solution.

3.4. Effect of Magnetic Field on Material Removal Rate

Several attempts have been done on magneto-electropolishing technique by investigating the effect of adding magnetic force into the process. A 1 T magnetic field was introduced to electropolishing on titanium workpiece, and the experimental results revealed that the electropolished surfaces have altered its mechanical properties in increased surface microhardness [41] and improved corrosion resistance by lowering the hydrogen content on the surface [42]. When applied to stainless steel, the magnetic force also indicated the same phenomenon [43].

The Lorentz forces due to presence of a magnetic field can create a mechanical effect that rotates the electrolyte around the direction of the magnetic field. In theory, this rotation could decrease the thickness of the diffusion layer, thus improving the material removal rate by increasing dissolution process [40]. However, in this study, although being a factor in increasing material removal rate, the magnetic field is not one impactful parameter as the applied voltage and concentration of ethanol in the electrolyte. According to the contribution ratio of magnetic field effect on removal rate, the 7.09% indicates that this parameter is not significant to achieve higher material removal. In electropolishing, there is no fit parameter set for all electropolishing setups [48]. Given different combination of electrode-electrolyte yield in different current-voltage relationship, and every modification added becomes another variable that has to be taken into account. In this study, based on the Taguchi analysis for yielding high removal rate, it can be concluded that magnetic force does not affect much on the removal rate. However, cases may be different when the work objective is changed.

4. Conclusions

In the present work, pareto ANOVA analysis based on Taguchi L9 orthogonal array was used to identify the optimum electropolishing parameters to achieve high material removal rate on titanium workpiece. Applied voltage, ethanol concentration, and magnetic field were considered as input machining parameters. The *S/N* ratio of the quality characteristics of the material removal rate was analyzed using the 'larger-the-better' criteria. From the three process factors considered to increase the material removal rate, it was found that the applied voltage has the highest influence followed by the ethanol concentration and the strength of the magnetic field. The optimum machining parameter values to maximize material removal rate are, applied voltage of 15 V and ethanol concentration of 20 vol.%. However, it was revealed from the pareto ANOVA analysis that the strength of magnetic field is not significant to enhance the material removal because the cumulative ratio of the applied voltage and ethanol concentration alone have surpassed 90%. For the continuation of this study, future work will consider the analysis of surface roughness (Ra) of the electropolished workpiece using Taguchi method.

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