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Precision Electropolishing on Fabricating SS 316L Microchannel – A Taguchi Approach

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Abstract – *This paper presents the fabrication of a microchannel on stainless steel 316L (SS 316L) by electropolishing method. Machining parameters such as applied voltage, concentration of NaCl in the electrolyte solution and machining gap between tool and workpiece have been optimized in this electropolishing process. The Taguchi method is adopted to ascertain the optimum process parameters in order to increase maximum material removal rate using L9 orthogonal array. Pareto analysis of variance is employed in order to analyze the machining process parameters to the material removal rate. The result shows that the optimal parameters to achieve the maximum material removal rate is by using a combination of 10 V as applied voltage, NaCl concentration of 15 wt.%, and setting 1 cm as the machining gap. It has been also found out that in order to have relatively high material removal without sacrificing the surface quality and the geometrical accuracy of the microchannel produced, applied voltage at 7 V, NaCl concentration of 7 wt.% and machining gap of 3 cm is the best combination of the electropolishing parameters.*

***Keywords**: Electropolishing, SS 316L, Taguchi, Manufacturing Innovation*

Nomenclature

V	Applied voltage
S/N Ratio	Signal to noise ratio
μ	Output mean
n	Number of runs
MRR	Material Removal Rate
EDM	Electrical Discharge Machining

I. Introduction

Stainless steel 316L (SS 316L) has been extensively used in biomedical devices due to its remarkable properties such as high biocompatibility, mechanical strength and corrosion resistance [1], [2]. SS 316L exhibits relatively good strength and corrosion resistance, a common choice for biomedical implants and pharmaceutical products where a minimum metallic contamination is often required. Microfilter is one of the applications of SS 316L used as a dialyzer of implantable artificial kidney [3]. The microfilter works as a dialyzer, an apparatus in which dialysis is carried out consisting essentially of one or more containers for liquids, which has a set of membrane and microchannel formed on SS 316L metallic sheet for solutions flow [4]. The dialyzer has consisted of wet-etched Titanium sheets that have formed a microchannel and a dialysis membrane, sandwiched in a microsystem in order to perform blood filtration [5]. Surface qualities of the microchannel and other metallic implants, specifically on its corrosion resistance, play an important role in their biocompatibility, performance and functionality [7]-[9].

Therefore, various advanced machining processes have been utilized in order to obtain high surface quality of the surface machined of metallic implants, especially when microchannel requires a complex micro-profile, including 3-dimensional printing [10], micro-electrical discharge machining (micro-EDM) [11], [12], electrochemical machining [13], additive manufacturing [14], to name a few. However, those machining processes often produce surface cracks and microvoids [15], [16]. Hence, surface modification is definitely needed in order to meet biocompatibility qualifications for implantable device [17]. However, in the fabrication of miniature products, roughing and finishing processes are often integrated into one process due to the tiny removal and the intricate shape. Microchannel for dialysis system has labyrinthine patterns with holes and small blood passages, formed over a thin biometallic sheet [18]. Micromachining processes such as micropunching cannot be utilized since direct machining will introduce mechanical stress on the machined sheet, affecting the surface properties and further reducing the performance of the microchannel. Therefore, it is advisable to use an advanced machining process where there is no contact between the tool cutter and the materials being machined. There are several advanced manufacturing processes that it is possible to produce such intrusion in a thin biometallic sheet. A wet-etching process, which uses liquid chemicals to remove materials from a wafer, is usually adopted for this case. The

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material is removed from the wafer where photoresist mask is not present, hence forming a negate intrusion of the photoresist mask. This method is low cost. However, it is difficult to control the removal mechanism especially when the final product should have a precise dimension and a qualified surface finish as a micro-implantable device. The other option is using electrical discharge machining process. This process is a stress free machining, where material is removed by means of a series of tiny, repeated electrical discharges between the two electrodes in the presence of dielectric fluid [19]. EDM offers a high machining efficiency amongst the other machining processes. However, the operating cost is high and it requires a specific mold to be used as the tool electrode [20]. It also suffers from the problems with surface integrity owing to the thermally induced defects.

Amongst advanced machining processes, electropolishing has been considered as a promising method to improve the biocompatibility of implant material by providing of high surface finish [21], [22], no tool wear and absence of thermally induced defects [23], [24]. Electropolishing is one of the advanced manufacturing processes that use Faraday's law principle to remove conductive materials such as stainless steel or similar alloys [25], [26]. In principal, electropolishing has a similar reaction with electrochemical machining, where the workpiece is normally selected as the anode, since it dissolves into the electrolyte solution. At the anode, workpiece surface experiences oxidation and then dissolves into the electrolyte solution [27], [28]. The reaction is described as follows:

$$M \rightarrow M^{n+} + ne^- \quad (1)$$

where n is the number of the electron released from metal atom during electrochemical reaction. Apart of the anodic reaction, oxygen evolution and formation of hydrogen ions as a result of electrolysis of water may also take place [27]. The reaction can be written as:

$$H_2O \rightarrow 2H^+ + {}^1\!/_2\, O_2 \uparrow + 2e^- \quad (2)$$

In the case of using non-passivating electrolytes, such as NaCl and NaBr, the development of halogen gases may occur [28], [29]:

$$2Br^- \rightarrow Br_2 \uparrow + 2e^- \quad (3)$$

At the cathode, different reactions take places based on the type of the electrolyte used. When the basic electrolytes are used, the liberation of hydrogen gas and local increase in alkalinity of the electrolyte solution is caused by the electrolysis of the water due to the formation of hydroxyl ions [28], [30]. During the anodic reaction, these hydroxyl ions reactions with the metallic ions are produced, and then they precipitate as sludge, which may deteriorate the stability of electrochemical process. Therefore, it is recommended to have acidic electrolytes in order to minimize the sludge precipitation [29], [31]:

$$2H_2O + 2e^- \rightarrow 2OH - + H_2 \quad (4)$$

$$M^n + nOH^- \rightarrow M(OH)_n \quad (5)$$

The electrochemical activity occurring between tool and the workpiece during electrochemical machining is illustrated in Fig. 1. Due to the nature of the material removal, most of the electropolishing researches have focused on perfecting surface quality during finishing process rather than material removal for roughing process.

However, electropolishing process combines chemical and electrical parameters, which somehow is challenging to synchronize the two in order to yield a high material removal rate and surface finish. The microchannel is formed on a thin biometallic sheet, and adding a small, intricate shape to produce the electropolishing process will be focused on material removal in order to make a final product.

In this work, electropolishing on SS 316L sheet has been performed in order to fabricate microchannel under different machining parameters, aiming to reach high material removal rate with sufficient surface finish. There have been three parameters to optimize, i.e. the applied voltage, the concentration of electrolyte solution, and the machining gap between the tool and the workpiece.

Taguchi statistical method has been utilized to determine the optimum machining parameters. The parameters have been analyzed using Pareto analysis of variance based on the respective material removal rate, geometry accuracy of the electropolished microchannel, and the surface quality produced.

The structure of this paper presents Section I describing material removal mechanism in electropolishing process. Section II deals with the details of material, experimental methods and statistical analysis used in this study. Section III focuses on the experiment results related to the effect of machining parameter on material removal rate based on statistical analysis.

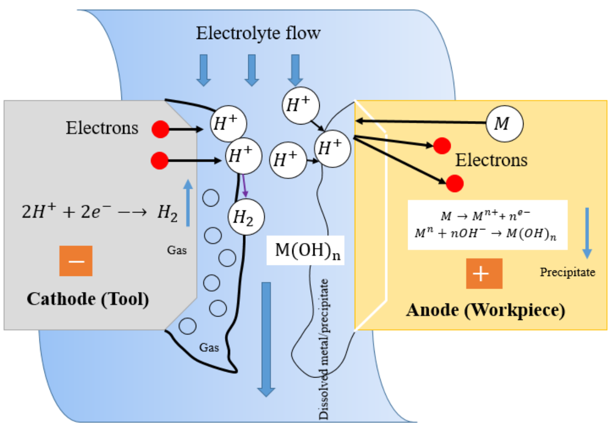


Fig. 1. Illustration of electrochemical activity in the inter-electrode gap during electrochemical machining (Redrawn from Modern machine shop)

II. Materials and Methods

This section presents the material used and the fabrication steps of microchannel on SS 316L sheet.

II.1. Material

Commercially available SS 316L sheets as the workpiece, and titanium sheets as the tool electrode, 200 µm in thickness, have been purchased from Nilaco Japan Co. Ltd. Sodium chloride (NaCl) has been purchased from CV. Alfa Kimia, Indonesia. Pure water has been mixed with NaCl at three different concentrations: 7% wt, 10% wt, and 15% wt, for the preparation of the electrolyte solution. DC power has been used to supply pulse voltage in order to provide energy for electropolishing process.

II.2. Fabrication of Microchannel on SS 316L Sheet

In this study, microchannel on SS 316L sheet has been fabricated using electropolishing method. Prior to the electropolishing process, SS 316L sheets have been covered by a patterned photoresist vinyl mask. It has acted as a protection film for area that would not be machined. The masked SS 316L sheet has been subsequently dipped into the electrolyte bath in order to start the electropolishing process. The masked SS 316L has acted as the anode, whilst the titanium has acted as the cathode. Figure 2 shows the detail fabrication of microchannel on SS 316L sheet using electropolishing method. In the electropolishing process, machining parameters such as the applied voltage, concentration of NaCl solution, and the machining gap play an important role in having maximum material removal rate. In order to increase the material removal rate, Taguchi statistical method has been used to determine the optimal process parameters. Statistical method has been considered as one of the best method to determine the optimum parameters for any kind application [32], [33]. Table I shows the machining parameters used in this work, whilst, electropolishing time has been set to 7 minutes.

III. Result and Discussions

III.1. Optimization of the Machining Parameters via Taguchi Method

Three parameters, applied voltage, NaCl concentrations in electrolyte solution, and machining gap between the tool and the workpiece, have been designed as factor A, factor B and factor C, consecutively. Each one consists of three levels. The levels of the factors for the experiments have been determined based on the results from the preliminary study.

TABLE I
MACHINING PARAMETERS OF ELECTROPOLISHING PROCESS

Voltage (V)	5, 7 and 10
NaCl concentration (wt. %)	7, 10 and 15
Machining gap (cm)	1, 2 and 3

Applied voltage is considered as qualitative parameters, and it has three levels, which are 5 V, 7 V and 10 V. The NaCl concentration in electrolyte has been fixed at three levels, i.e. 7 (wt. %), 10 (wt. %) and 15 (wt. %).

For the machining gap between the tool and the workpiece, the first, the second, and the third levels have been 1 cm, 2 cm, and 3 cm.

The detail of the level of machining parameters is shown in Table II. In order to determine the effect of each variable to the material removal rate, the signal to noise (S/N) ratio is employed. In the S/N ratio, three characters can be used: the-smaller-the-better, the-nominal-the-best, and the-larger-the-better. For the material removal rate, the larger the better type characteristic (Equation (6)) is used because maximum material removal rate is desirable.

$$S/N = -10\log\left[\frac{\sum\frac{1}{\mu^2}}{n}\right] \tag{6}$$

Material removal rate and the S/N ratio of each machining parameters combination are shown in Table III. Based on the value of material removal rate presented in Table III, the average of S/N ratio level for each factor is summarized in Table IV.

TABLE II
FACTORS AND THEIR LEVELS OF PARAMETER IN ELECTROPOLISHING PROCESS

Symbol	Control factor	Levels 0	1	2
A	Voltage (V)	5	7	10
B	NaCl concentration (wt. %)	7	10	15
C	Machining gap (cm)	1	2	3

TABLE III
RESULTS OF THE MATERIAL REMOVAL RATE AND S/N RATIO IN ELECTROPOLISHING PROCESS

Exp. No.	Experiment factors*			MRR (mg/s) Noise factor			Mean	S/N Ratio (dB)
	A	B	C	N0	N1	N2		
1	A0	B0	C0	1.48	1.13	0.82	1.14	0.41
2	A0	B1	C1	0.56	0.89	0.99	0.81	-2.61
3	A0	B2	C2	0.97	1.15	1.01	1.04	0.3
4	A1	B0	C1	1.35	1.35	1.39	1.36	2.69
5	A1	B1	C2	1.25	1.39	1.42	1.35	2.59
6	A1	B2	C0	1.34	1.29	1.27	1.30	2.27
7	A2	B0	C2	1.35	1.5	1.37	1.41	2.94
8	A2	B1	C0	2.49	2.51	2.7	2.57	8.17
9	A2	B2	C1	2.46	2.62	2.57	2.55	8.12

Note: *refer to Table II

TABLE IV
AVERAGE S/N RATIO BY FACTOR LEVELS (dB) FOR MATERIAL REMOVAL RATE IN ELECTROPOLISHING PROCESS

	Factor* A	B	C
Level 0	-0.63	2.01	3.62
Level 1	2.52	2.72	2.73
Level 2	6.41	3.56	1.94
Max-Min	7.04	1.55	1.68
Average	2.76	2.76	2.76

*Factors and levels was described in Table II

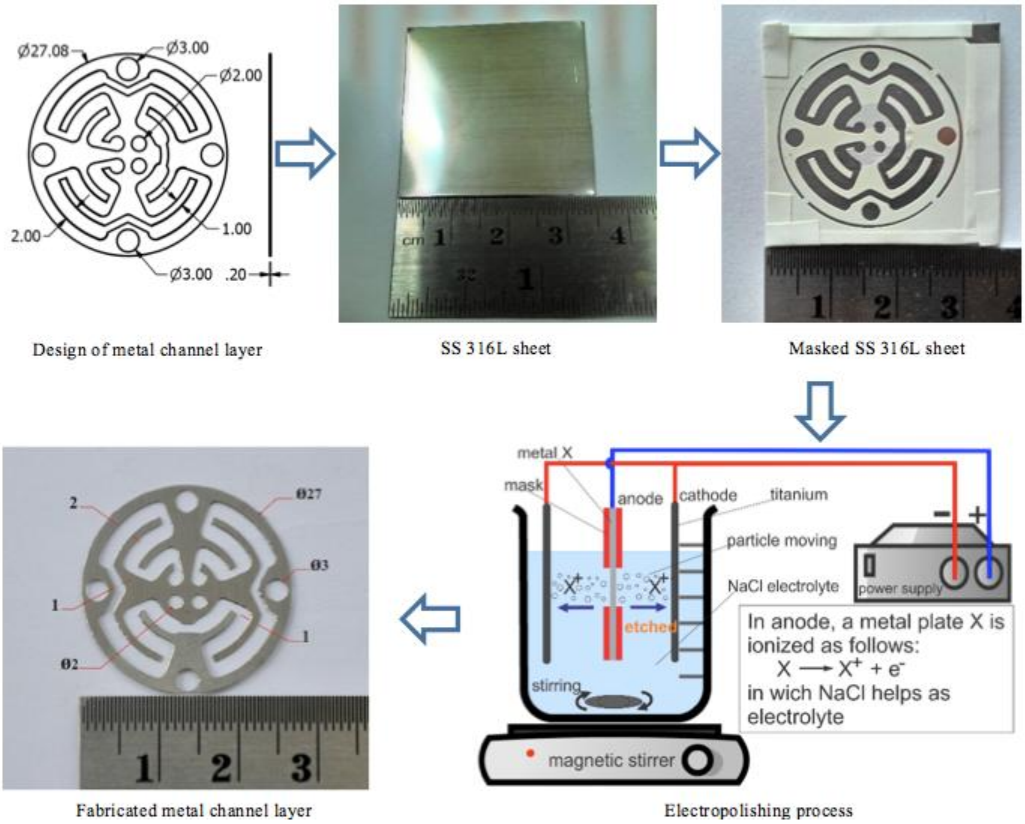


Fig. 2. Fabrication steps of microchannel on SS 316L using electropolishing

III.2. Combination of Optimal Levels for Each Factor

The aim of this study is to increase the material removal rate by determining the optimum level for each factor. It can be determined by the level with the highest S/N ratio value. Based on the data presented in Figure 3, the optimum combination of each factor is A3B2C0. This means that the optimal levels are A3 (voltage is 10 V), B2 (NaCl concentration is 15 wt. %), and C0 (machining gap is 1 cm) and the combination of those machining parameters has a significant effect in achieving maximum material removal rate. The results of the optimum machining parameters are summarized in Table V.

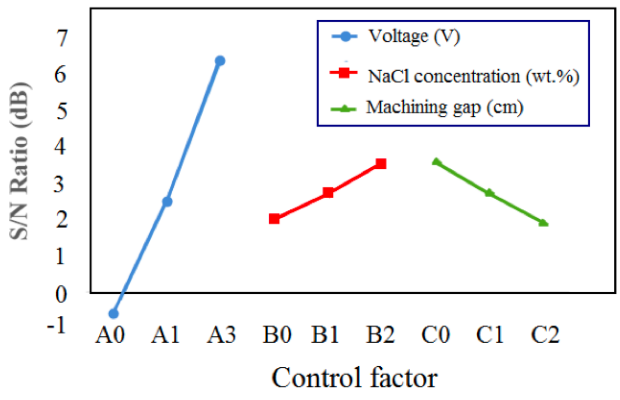


Fig. 3. The-larger-the-better S/N Graph for material removal rate in electropolishing process

TABLE V
OPTIMAL CONDITIONS FOR PARAMETERS
IN ELECTROPOLISHING PROCESS

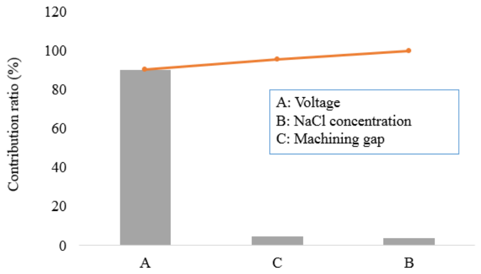
Factor	Level
A. Voltage (V)	10
B. NaCl concentration (wt. %)	15
C. Machining gap (cm)	1

III.3. Effects of Voltage on Material Removal Rate

Pareto analysis of variance (ANOVA) has been utilized to determine the influence rate of each parameter. ANOVA analysis method is suitable for the study due to its effectiveness in analyzing the results of the design parameters.

Figure 4 shows the Pareto ANOVA of the material removal rate for electropolishing process. The most significant factor has been chosen from the left-hand side of Pareto diagram, which is cumulatively around 90 % of the total contribution. In addition, it can be seen that applied voltage from DC power supply is significant (90.5%) in order to obtain the highest material removal rate.

The contribution of the voltage parameters in this experiment has already exceeded 90% as shown in Figure 3. Hence, it is clear that the voltage has a recognizable impact in achieving high MRR. It has been in agreement with Schubert et al. [34] and Qi et al. [35], that higher voltages have produced higher material removal since the voltage is required to energize the electrolytic reactions.



	A	C	B
Contribution ratio (%)	90.5	5.1	4.4
Cumulative contribution ratio (%)	90.5	95.6	100

Fig. 4. Pareto ANOVA Analysis for material removal rate in Electropolishing process

III.4. Effects of Voltage on the Accuracy of the Channel

Applying voltages at different levels gives different results in term of surface quality of the fabricated microchannel. The fabricated channel from electropolishing processed at 5 V shows that some parts of the channel have not been fully etched, as shown in Figures 5(a)-(c). When the output voltage has been increased to 7 V, the channel of SS 316L sheet has been completely etched without leaving any part of the metal in the channel, as seen in Figures 5(d)-(f). Increasing the applied voltage to 10 Volt has yielded different result.

The combinations of the applied voltage of 10 Volt and the machining gap of 3 cm provide a relatively accurate geometry channel, as shown in Figure 5(g).

However, when the machining gap has been reduced to 1 cm and 2 cm at constant 10 V, the SS 316L sheets have been entirely etched without leaving any part of it, as shown in Figures 5(h)-(i). Figures 6 show the cross sectional SEM images with different combinations of machining parameters used in electropolishing of SS 316L sheet. As seen in Figures 6(a)-(c), using output voltage of 5 V, the surface machined has not been flat and coarse grains appear on its surface. This can be explained because the voltage applied has not been sufficient to etch completely the metal layer channel. The number of coarse grains has reduced with the increase level of voltage applied, which is 7 V, as shown in Figures 6(d)-(f). High quality surface has been produced at applied voltage of 7V, NaCl concentration of 7 wt. % and machining gap at 3 cm, as can be seen in Figure 6(g).

Employing output voltage of 10V with NaCl concentration of 10 wt. % and 15 wt. % combined with machining gap at 1 cm and 2 cm, coarse grains and hills has appeared along in the middle of the surface machined, as seen in Figures 6(h)-(i). The possible cause of this "peak" line is because the removal of material has come fast from two directions, leaving a wavy surface on the processed sheet.

III.5. Effects of Machining Gap on Material Removal Rate

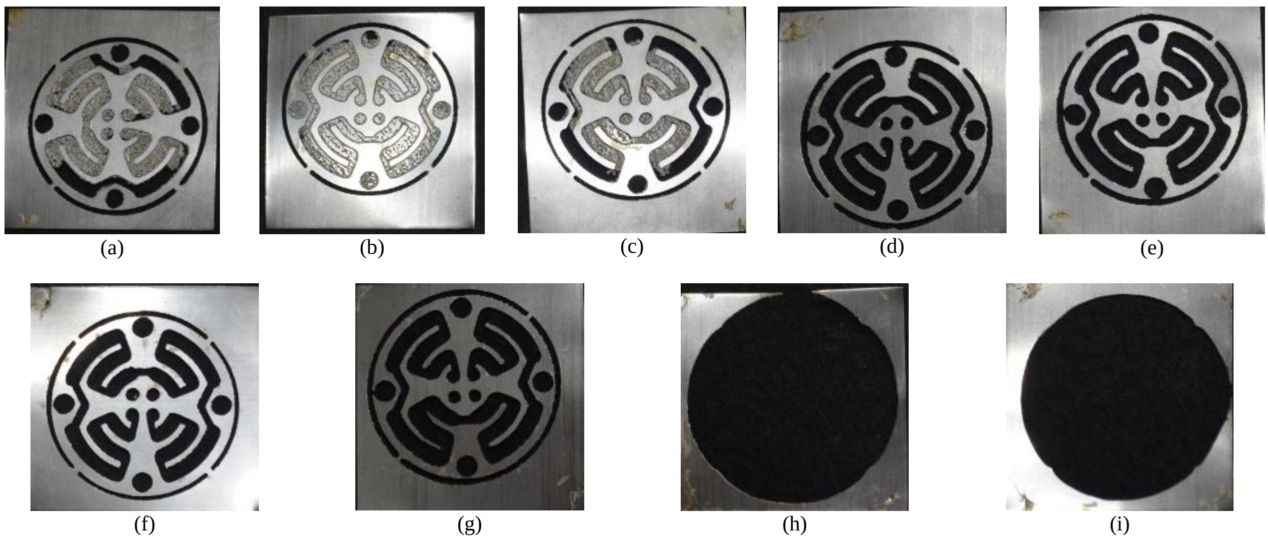
Figure 4 reveals that the distance of the machining gap is the least significant factor (5.1%) in increasing material removal rate. Therefore, even at the smallest machining gap of 1 cm, some parts of the channel have not been completely etched, as shown in Figure 5(c).

Furthermore, the wall surface produced on SS 316L microchannel is not smooth and not uniformly processed.

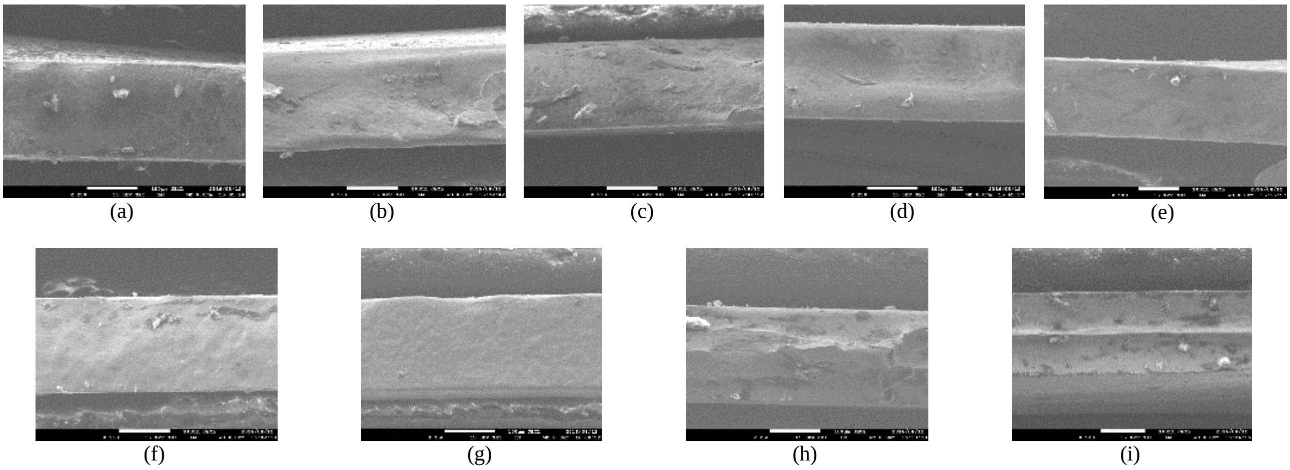
The same trends have been found out by Schubert et al. [34] and Natsu et al. [36] where larger working gaps have reduced material removal rate, and at small working gaps, the machining accuracy has decreased.

III.6. Effects of NaCl Concentration on Material Removal Rate

Figure 4 shows that the concentration of NaCl is insignificant (4.4%) to increase the material removal rate.



Figs. 5 Combination of machining parameters used in electropolishing of SS 316L metal layer (a) 5 V, 7 wt.%, 1 cm; (b) 5 V, 10 wt.%, 2 cm; (c) 5 V, 15 wt.%, 3 cm; (d) 7 V, 7 wt.%, 2 cm; (e) 7 V, 10 wt.%, 3 cm; (f) 7 V, 15 wt.%, 1 cm; (g) 10 V, 7 wt.%, 3 cm; (h) 10 V, 10 wt.%, 1 cm; (i) 10 V, 15 wt.%, 2 cm



Figs. 6. Cross section SEM images of different combination of machining parameters used in electropolishing of SS 316L metal layer (a) 5 V, 7 wt.%, 1 cm; (b) 5 V, 10 wt.%, 2 cm; (c) 5 V, 15 wt.%, 3 cm; (d) 7 V, 7 wt.%, 2 cm; (e) 7 V, 10 wt.%, 3 cm; (f) 7 V, 15 wt.%, 1 cm; (g) 10 V, 7 wt.%, 3 cm; (h) 10 V, 10 wt.%, 1 cm; (i) 10 V, 15 wt.%, 2 cm

At the highest concentration of NaCl used, which is 15 wt.%, some parts of the channel which should have been etched within 7 minutes, still remain, as shown in Figure 5(c). This is in agreement with Speidel et al. [37], where the increase of the concentration of sodium chloride has resulted in higher material removal rate due to higher conductivity and therefore higher current at constant voltage. This is due to the fact that variations in the concentration of NaCl solution used in this study have been too low to give a remarkable impact in removing the material from the SS 316L sheet. The variation of NaCl concentration used also has no significant effect on producing high surface quality channel. Figure 5(a) shows that NaCl solution of 7 wt. % has produced surface with coarse grains. The same results occur when employing NaCl solution of 15 wt. %, where some grains appear on the surface. This result is in accordance with the research conducted by Núñez et al. [38], where the variation of electrolyte concentration had no significant effect on the surface quality produced.

IV. Conclusion

In this study, the optimization of machining parameters in electropolishing process for the fabrication of SS 316L microchannel has been successfully demonstrated. The effects of applied voltage, NaCl concentration, and machining gap on material removal rate have been investigated. Using Taguchi's L9 Orthogonal arrays for experimental design, electropolishing process has been carried out in fabricating microchannel on SS 316L sheet. The parameters of interest have been applied voltage, NaCl concentration, and machining gap. Taguchi’s signal-to-noise ratios have been calculated in order to obtain optimum machining parameters for material removal rate. Analysis of Variance (ANOVA) has been used to determine any statistically significant machining parameter. The optimum parameters obtained for achieving maximum material removal rate are voltage of 10 V, machining gap of 1 cm, and NaCl concentration of 15%. For having better surface, quality and geometrical accuracies have been found to be voltage of 7 V, NaCl concentration of 7 % and machining gap of 3 cm.

This study has comprehensively shown that electropolishing process has high potential to machine advanced metallic alloys with a labyrinthine pattern due to the absences of thermal defects and its capabilities to fabricate complex micro-shape. Moreover, in electropolishing, high surface quality and precision material removal can be obtained by power source, machining gap and concentration of electrolyte.

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References

[1] S. Morais, J.P. Sousa, M.H. Fernandes, G.S. Carvalho, J.D. De Bruijn, C.A. VanBlitterswijk, Effects of AISI 316L corrosion products in in vitro boneformation, *Biomaterials*, vol. 19, June 1998, pp. 999 – 1007.

[2] H. Hendra, R. Dadan, J.R.P. Djuansjah, *Metals for biomedical applications*, Biomedical Engineering-From Theory to Applications, (InTechPublisher, 2011)

[3] G.S. Prihandana, H. Ito, K. Tanimura, H. Yagi, Y. Hori, O. Soykan, N. Miki, Solute diffusion through fibrotic tissue formed around protective cage system for implantable devices, *Journal of Biomedical Materials Research*, vol. 103(6), Aug. 2015, pp. 1180 –1187.

[4] Y. Gu, N. Miki, Multilayered microfilter using a nanoporous PES membrane and applicable as the dialyzer of a wearable artificial kidney, *Journal of Micromechanics and Microengineering*, vol. 19, May 2009, 065031.

[5] N. To, I. Sanada, H. Ito, G. S. Prihandana, S. Morita, Y. Kanno, N. Miki. Water-permeable dialysis membranes for multi-layered microdialysis system, *Frontiers in Bioengineering and Biotechnology*, vol. 3(70), June 2015, pp. 70.

[6] C.C. Shih, C.M. Shih, Y.Y. Su, L.H.J. Su, M.S. Chang, S.J, Lin, Effect of surface oxide properties on corrosion resistance of 316L stainless steel for biomedical applications, *Corrosion Science*, vol. 46, February 2004, pp. 427 – 441.

[7] H. Hocheng, P.S. Kao, Y.F. Chen, Electropolishing of 316L stainless steel for anticorrosion passivation, *Journal of Materials Engineering and Performance,* vol. 10, 2001, pp. 414 – 418
[8] W. Zhou, X. Zhong, X. Wu, L. Yuan, Z. Zhao, H. Wang, Y. Xia, Y. Feng, J. He, W. Chen, The effect of surface roughness and wettability of nanostructured TiO2 film on TCA-8113 epithelial-like cells, *Surface and Coatings Technology,* vol. 200, May 2006, pp. 6155 – 6160.
[9] Chen, X., Dispensed-Based Bio-Manufacturing Scaffolds for Tissue Engineering Applications, (2014) *International Journal on Engineering Applications (IREA)*, 2 (1), pp. 10-19.
[10] Ahmad, M., Tarmeze, A., Abdul Rasib, A., Capability of 3D Printing Technology in Producing Molar Teeth Prototype, (2020) *International Journal on Engineering Applications (IREA)*, 8 (2), pp. 64-70.
doi: https://doi.org/10.15866/irea.v8i2.17949
[11] G.S. Prihandana, M. Mahardika, T. Sriani, Micromachining in Powder-Mixed Micro Electrical Discharge Machining, *Applied Sciences,* vol. 10(11), May 2020, pp. 3795
[12] G.S. Prihandana, T. Sriani, M. Mahardika, M. Hamdi, N. Miki, Y.S. Wong, K. Mitsui, Application of powder suspended in dielectric fluid for fine finish micro-EDM of Inconel 718, *The International Journal of Advanced Manufacturing Technology,* vol. 75(1), July 2014, pp. 599 – 613.
[13] X. Qi, X. Fang, D. Zhua, Investigation of electrochemical micromachining of tungsten microtools, *International Journal of Refractory Metals and Hard Materials,* vol. 71, February 2018, pp. 307–314.
[14] Rosli, N., Alkahari, M., Ramli, F., Sudin, M., Maidin, S., Single Layer Formation of Plasma Based Wire Arc Additive Manufacturing, (2020) *International Journal on Engineering Applications (IREA)*, 8 (3), pp. 89-95.
doi: https://doi.org/10.15866/irea.v8i3.17953
[15] G.S. Prihandana, M. Mahardika, M. Hamdi, K. Mitsui, , Accuracy improvement in nanographite powder-suspended dielectric fluid for micro-electrical discharge machining processes, *The International Journal of Advanced Manufacturing Technology,* Vol. 56, January 2011 pp. 143-149.
[16] G.S. Prihandana, M. Mahardika, , M. Hamdi, K. Mitsui, Effect of low-frequency vibration on workpiece in EDM processes, *Journal of Mechanical Science and Technology,* vol. 25(5), January 2011, pp. 1231-1234.
[17] J.C. Palmaz, New advances in endovascular technology, *Texas Heart Institute Journal*, vol. 24, 1997, pp. 156 – 159.
[18] G.S. Prihandana, Y. Nishinaka, H., Ito, Y., Kanno, N. Miki, Permeability and blood compatibility of nanoporous parylene film-coated polyethersulfone membrane under long term blood diffusion, *Journal of Applied Polymer Science,* vol. 131(6), October 2014, 40024.
[19] G.S. Prihandana, T. Sriani, M. Mahardika, M. Hamdi, N. Miki, Y.S. Wong, K. Mitsui, Application of powder suspended in dielectric fluid for fine finish micro-EDM of Inconel 718, *The International Journal of Advanced Manufacturing Technology,* vol. 75(1), July 2014, pp. 599 – 613.
[20] G.S. Prihandana, M. Mahardika, M. Hamdi, Y.S. Wong, N. Miki, K. Mitsui, Study of workpiece vibration in powder-suspended dielectric fluid in micro-EDM processes, *International Journal of Precision Engineering and Manufacturing,* vol. 14(1), October 2013, pp. 1817 – 1822.
[21] P.Tyagi, D. Brent, T. Saunders, T. Goulet, C. Riso, K. Klein, F.G Moreno, Roughness Reduction of Additively Manufactured Steel by Electropolishing, *The International Journal of Advanced Manufacturing Technology*, vol. 106, December 2019, pp. 1337–1344.
[22] P.Tyagi, T. Goulet, C. Riso, F.G Moreno Reducing surface roughness by chemical polishing of additively manufactured 3D printed 316 stainless steel components, *The International Journal of Advanced Manufacturing Technology,* vol. 100, October 2018, pp. 2895–2900.
[23] S.J. Lee, J.J. Lai, The effects of electropolishing (EP) process parameters on corrosion resistance of 316L stainless steel, *Journal of Materials Processing Technology,* Vol. 140, September 2003, pp. 206-210.
[24] E. S. Lee, Machining characteristics of the electropolishing of stainless steel (STS316L), *The International Journal of Advanced Manufacturing Technology,* Vol. 16, 2000, pp. 591–599.
[25] J.A. McGeough, *Principles of Electrochemical Machining,* CRC Press, 1974.
[26] G.S. Prihandana, M. Mahardika, Y. Nishinaka, H. Ito, Y. Kanno, N. Miki, Electropolishing of Microchannels and its Application to Dialysis System, *Procedia CIRP,* vol. 5, March 2013, pp. 164 – 168.
[27] P.C. Pandey, *Modern Machining*; Tata McGraw-Hill Publishing Company Limited, 1980.
[28] S.S. Joshi, D. Marla, *Electrochemical Micromachining*, vol. 11, Elsevier, 2014.
[29] K.K. Saxena, J. Qian, D. Reynaerts, A review on process capabilities of electrochemical micromachining and its hybrid variants, *International Journal of Machine Tools and Manufacture,* vol. 127, April 2018, pp. 28–56
[30] Wilson, J. F. *Practice and Theory of Electrochemical Machining*; R.E. Krieger Pub. Co, 1982.
[31] S. Sharma, V.K. Jain, R. Shekhar, Electrochemical drilling of inconel superalloy with acidified sodium chloride electrolyte, *The International Journal of Advanced Manufacturing Technology,* vol. 19(7), April 2002, pp. 492–500.
[32] Ayyala, D., Chehab, G., Daniel, J., Sensitivity of M-E PDG Level 2 and 3 Inputs Using Statistical Analysis Techniques for New England States, (2018) *International Journal on Engineering Applications (IREA)*, 6 (5), pp. 169-178.
doi: https://doi.org/10.15866/irea.v6i5.16631
[33] Besarati, S., Atashkari, K., Hajiloo, A., Nariman-zadeh, N., Nikpey, H., Multi-Objective Pareto Robust Design of PID Controllers for Variable Compression Ratio Engines Using Genetic Algorithms, (2018) *International Journal on Engineering Applications (IREA)*, 6 (6), pp. 211-220.
doi: https://doi.org/10.15866/irea.v6i6.16999
[34] A. Schubert, M. Hackert-Oschatzchen, G. Meichsner, M. Zinecker, A. Martin, Evaluation of the influence of the electric potential in jet electrochemical machining. *In: 7th International Symposium on Electrochemical Machining Technology (INSECT),* vol 1, 2011, pp 47–54. book 1
[35] X. Qi, X. Fang, D. Zhua, Investigation of electrochemical micromachining of tungsten microtools, *International Journal of Refractory Metals and Hard Materials,* vol. 71, February 2018, pp. 307–314.
[36] W. Natsu, T. Ikeda, M. Kunieda Generating complicated surface with electrolyte jet machining. *Precision Engineering, vol. 31(1),* January 2007, pp. 33–39.
[37] A. Speidel, J. Mitchell-Smith, D.A. Walsh, M. Hirsch, A. Clare, Electrolyte jet machining of titanium alloys using novel electrolyte solutions. *Procedia CIRP,* vol. 42, 2016, pp. 367–372.
[38] P.J. Núñez, E. García-Plaza, M. Hernando, R. Trujillo, Characterization of Surface Finish of Electropolished Stainless Steel AISI 316L with Varying Electrolyte Concentrations, *Procedia Engineering,* vol. 63, 2013, pp. 771-778.

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