A Study on the Development of the Electrolytic-deburring System and Characteristics of the Micro deburring
의료용 Stent 마이크로 전해디버링 시스템 개발 및
디버링에 관한 연구

A Study on the Development of the Electrolytic-deburring System and
Characteristics of the Micro deburring

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ABSTRACT

Stent is derived from Charles R. Stent, dentist of UK, who developed material for dental mould. After that time, stent is designated as a structure that support living body tissue. Recently it is designated as a high polymer or metal tube that expand the inner parts of the body when it is stenosed. Electrolytic-deburring has a same principle of electropolishing. Electropolishing is an process to make a surface planarization using an electrochemical reaction with low current density. It can provide a smooth, bright and reflective surface that exhibits superior corrosion resistance when the workpiece (+) and tool electrode (-) are electrically charged. Electropolishing is a load free machining so it is suitable for the polishing of both complex shapes and hardened materials, which are difficult to machine mechanically, because in electropolishing the electrode and the workpiece are not in contact with each other. The mechanism of electropolishing has not yet been fully determined, but it is usually explained as follows. As the voltage increase, the emulsion which contain high specific gravity, viscosity and electric resistance, is created by the ion eluted from workpiece. In this study, the medical stent electrolytic-deburring system is developed and the experiment is performed. Through the preliminary experiment the machining condition is selected about nitinol material. Basis of this preliminary experiment, the system is designed and developed. As a result of the experiment, the optimization electrolytic-deburring condition is 1mm electrode gap, 3A current and 60s machining time.
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Chapter 1. Introduction

1.1 Background of Study

Stent is derived from Charles R. Stent, dentist of UK, who developed material for dental mould. After that time, stent is designated as a structure that support living body tissue. Recently it is designated as a high polymer or metal tube that expand the inner parts of the body when it is stenosed. To use the stent for expanding the inner parts of the body, the diagnostic radiology should be preceded because of the correct placing of the stent. This diagnostic radiology was possible after the development of fluoroscopy in 1950s, the fluoroscopy enable the monitoring of the inner parts of the body real time. In 1969, Carles T. Dotter succeeded in the insertion of stainless steel stent that is coil shape in dog's artery. In 1985, clinical trial began in earnest by Wright developed Gianturco Zig-Zig shape stent. The same year Palmaz developed a stent that is expanded after compressed balloon insertion.[1]

This stent operation is more convenient than the surgical operation, can reduce the onus of general anesthesia and have a high success rate so it can be applied to the people who is troublesome of general anesthesia with a cardiac disorder, respiratory ailments.

Stent is much used in case of iliac artery, carotid artery, renal artery, coronary artery. Among them coronary artery is a bone of death in the West and it is increased steady in Korea because of the change of dietary life as West. So the interest and operation about intracoronary stenting, simple and convenient
operation, increase rapidly. But if the intracoronary stenting is operated about the coronary artery, 20% of the instent restenosis recur. And the stent lead to the injury of endothelium, and stimulate the intima tissue constantly. The injury and simulation caused by stent bring about the neointimal hyperplasis of new tissue and it may cause the instent restenosis of a blood vessel in chronicity. This instent restenosis problem is a focus of study about coronary artery disease and to prevent this problem, development of the new design stent, drug eluting stent, improving of surface roughness and deburring is performed now.[2]

In this study, the Electrolytic-deburring system for Nitinol stent after the laser cutting is developed and the experiment is performed.
1.2 Contents of Study

The death rate in the West have increased gradually and domestic death rate also increase as the eating habits change to the West. So the number of the death caused by the coronary artery disease have increased 6 times during last 10 years. Instent restenosis is a big problem during intracoronary stenting. So the interest of stent, the inner parts of the body friendly, development has increased. This study contents about followings.

1) Development of the Electrolytic-Deburring System for Stent
   - Conception of the System and Design
   - Making the System

2) Experiment
   - Electrolytic-Deburring process design to make the stent
   - Preliminary experiment of Nitinol metal to select the optimize experiment conditions
   - Experiment of the Electrolytic-Deburring
Chapter 2. Medical Stent

2.1 Type of Stent

To insert conveniently stent into the inner parts of the body, the blood vessel, the gullet or the internal organs etc., the stent should be compressed as small section area and it is a way to decrease the pain of patient. After inserting into the part of the illness, the stent should be expanded to expand the stenosis part. There are two kinds of stent, self-expandable and balloon-expandable stent. The self-expandable stent use the expand force of metal not the exterior force. The balloon-expandable stent use the balloon force, namely exterior force.

The self-expandable stent is a typical thing that use a elastic force of metal. The stent delivery method is as following. Stretch the stent to make the section area small and insert the stent into the delivery system tube. Using the delivery system, placing the stent at the stenosis part. After the drawback the delivery system, the stent is expanded caused by the elastic force of itself. Song-stent, Hanaro-stent and Wall-stent use this principle.

The balloon-expandable stent has a structure that can be compressed on expanding state and can be expanded using the balloon expandable force that is inner. So the stenosis part is expanded.[3]
Fig. 2-1  CYPHER™ Sirolimus-eluting Coronary Stent: sirolimus (drug) emitting inside an artery
Fig. 2-2 Balloon Catheter (After): Once in position, the balloon is inflated, pushing the plaque against the wall and enlarging the opening of the artery.

Fig. 2-3 Expanded Stent: Expanded stent prevents a previously blocked artery from re-closing.
2.2 Stent Material

As the stent use the elastic force to expand and compress, the material is mostly metal. The stainless steel used at the first time and the nitinol is used much recently because of its super-elasticity and shape memory characteristics. The super-elasticity characteristic of nitinol decrease the deformation and destruction of the stent and has a low friction resistance during the stent insertion. It is very easy to compress with the cold water and the compressed stent expand easily because of the body temperature when it is placed the inner body. Besides this material, there are some material for the stent such as Tantalum and Cobalt alloy. The metal material of stent should has not only the proper elastic force but also the large atomic weight to be showed by X-ray. Also stent should not be eroded in the body and it is necessary that low a blood clot in short term and should not has an immune reaction excessively with circumference tissue in long term.[4]
2.3 Design demands

The stent must satisfy the following design demands.[5]

1) Clinical Demands
   - Sufficient radial force from each strut to ensure vessel patency
   - Regain its initial shape after compression due to the super-elastic property of the nitinol material
   - Conform smoothly to the anatomy and no injure the arterial wall
   - Track-ability and push-ability to reach and cross target lesions

2) Mechanical Demands to satisfy Clinical Demands
   - Must maintain its cylindrical shape when bent 180 degrees
   - Have flexibility to smoothly follow various anatomical bends
   - Have a smooth surface that does not injure the arterial wall
   - Must not lose its expanding force to ensure vessel patency when it expands 3-6 times
   - Have substantial axial length when it expands 3-6 times
   - Must also bend smoothly and follow various bending vessels if built into a catheter (2 mm in diameter)
2.4 Stent Fabrication Technology

Until now several methods have been used for metallic stent processing, but the laser processing methods has various advantages over the conventional etching and electro-forming techniques. In the etching technique, the formation of 'etching lip' may lead to undesirable side effects, whereas in the laser processing method which produces the straight edge with desired taper, results in a uniform fluid flow in the blood vessel. In the recent, past several configurations of Nd-YAG lasers in pulse or Q-switch mode operation have been applied for the stent processing. But of these, the short pulse Nd-YAG laser with higher pulse repetition rate has shown the promising results with respect to quality and the economical viability. Short pulse width is advantageous in reducing the heat affected zone. It also serves to heat the irradiated volume to the vaporization temperature in a time scale shorter than that for the heat to diffuse in the surrounding. In the metallic stent technology one faces the problems of biocompatibility, dross adherence and heat affected zone, etc. These problems can be addressed with the polymer stent, which exhibits several advantages over the metallic stent technology. However, for the polymer materials the appropriate wavelength for processing is in the UV-region. Nd-YAG laser system operating at third harmonic or excimer laser is best suited for such applications. Recently, this technique has been applied for processing of the next generation biopolymer stent, but the initial results are still at preliminary stages.[6]
2.5 Laser Cutting Procedure

The experiments were performed using a short pulse Nd-YAG laser. Prior to processing, CAD data of the stent with the desired configuration is generated and this data is fed to the laser processing system. To fabricate the metallic stent, first the hollow metallic tube is mounted on the lathe through the inner diameter of the tube. Then, the cutting of the desired pattern is performed by programming the whole process, thereby the tube is rotated and moved longitudinally relative to the laser.

Fig. 2-4 Laser cutting procedure
2.6 Dross Adherence and Removal Process

During the laser processing of the stent, one encounter with the problem of dross, burrs and spatter adherence to the underside of the cut. This is due to the three reasons.

1) Temperature gradient caused by the laser beam from top to bottom surface of the work-piece
2) Beam divergence from top to bottom results in larger kerf width underneath as a result more material is melted in the lower side
3) With the increase in depth of the cut, gas jet becomes turbulent and its pressure reduces, thus allowing dross to adhere.

Therefore, the processed sample is no free from dross, spatter and corrosion. In order to overcome this problem, basically the following techniques were applied that yielded the most effective results.

2.7 Acid pickling

Acid pickling is an effective method for the chemical removal of surface oxides and other contaminants from metallic materials by immersion in an aqueous acid solution. The stents were covered with oxide scales and slag after laser cutting. Soap wash by spray of soap water was given to the laser cut stents to remove
dust particles, oil, grease and slag. Stent is then cleaned with a spray of deionized water to remove soap.

2.8 Electrolytic-Deburring

Electrolytic-Deburring is the electrolytic removal of metal in a highly ionic solution. By adjusting the electrode voltage and current, together with the chemistry of the etching solution, electrolytic-deburring can achieve a smoother metal surface than chemical or acid etching alone.
Laser machining

Dross adherence and removal

Pickling technique

Soft etching

Electropolishing

Fig. 2-5 Stent fabrication process
Chapter 3. Theory of Electrolytic-Deburring

3.1 Principle of Electrolytic-Deburring

Electrolytic-deburring has a same principle of electropolishing. Electropolishing is an process to make a surface planarization using an electrochemical reaction with low current density. It can provide a smooth, bright and reflective surface that exhibits superior corrosion resistance when the workpiece (+) and tool electrode (-) are electrically charged. Electropolishing is a load free machining so it is suitable for the polishing of both complex shapes and hardened materials, which are difficult to machine mechanically, because in electropolishing the electrode and the workpiece are not in contact with each other. The mechanism of electropolishing has not yet been fully determined, but it is usually explained as follows. As the voltage increase, the emulsion which contain high specific gravity, viscosity and electric resistance, is created by the ion eluted from workpiece. Then, the emulsion cover the depression(凹) of the surface and it obstruct the elution of the depression. In result surface planarization is completed as the prominence(凸) is firstly eluted.[7]

By osmosis, the metal ion in solution at the edge of the anode film will naturally migrate into the main body of the solution. This loss of ions into the main body of the solution reduces the ion concentration of the electropolishing solution at the surface of the anode film. Fig. 3-6 shows that the outer later of the anode film becomes more active than the inner layer. This creates a situation where metal can still be removed in the regions of the anode film with a high charge.
concentration farthest away from the surface of the workpiece. As electropolishing take place, oxygen is formed as a natural part of the process. The oxygen is generated at the outermost edge of the anode film since this oxygen is generated as a gas, it will form bubbles and moves the main body of the electropolishing solution along the surface of the anode film. With this movement of reducing its outer layer, the highest spots of the workpiece surface will be dissolved faster while the lower regions of workpiece are inaccessible. But in the event that a high current is applied, a great amount of oxygen bubble formation occurs and it leaves pit marks on the work surface that may contain impurities.

During anode dissolution, a polarization curve can be obtained both the tool electrode and workpiece are positioned close together and the applied current is increased. For anode potentials in the AB range, the metal surface becomes etched, when the anode potential becomes greater than B in the BC range, an oxide film may be formed suddenly on the anode. In the CD range, named the 'Plateau region' where the electropolishing effect take place, there is hardly any change in current density as the voltage increases. When the electropolishing process is carried out quickly because high current is applied, it leaves surface defects such as pits; hence, a current in the plateau region is usually used. However, it should also be pointed out that an applied current slightly higher than one in the plateau region is actually required. Therefore the plateau region in electropolishing is no the best range to achieve the best electropolishing, but the applied current density is a more important parameter.[8]

The passivation film formed at the anode surface is a very thin oxidisation film caused by result of reaction of metal ion(+) and electrolyte ion(-). Once this passivation film is formed, electro chemical reaction is slow down and finally
stopped because passivation film obstruct the electrolyte ion to reach to the metal surface. Therefore, to continue the machining by the electro chemical reaction it is desirable to remove the passivation film.

The electric resistance of electrolyte $R$ and specific conductivity $\sigma$ as follow equation.

\[ R = \frac{\mathcal{A}}{s} \quad (3-1) \]

\[ \sigma = \frac{1}{r} [\Omega^{-1} \cdot \text{cm}^{-1}] \quad (3-2) \]

where, $s [\text{㎠} ]$ is the cross section of electrode, $l [\text{㎝}]$ is the gap between anode and electrode, $r [\Omega \cdot \text{cm}]$ is the specific resistance. The electric resistance $R$ can be defined using the specific conductivity as follow.

\[ R = \frac{l}{\sigma} \quad (3-3) \]

The specific conductivity is closely connected with the concentration of electrolyte and the specific conductivity is larger as the concentration increase.

There are two kinds of electrolyte, activated and inert. In ultra precision machining the inert electrolyte is used because it makes a oxide film.

When the voltage $E$ is applied to the both ends in electrolyte, the current and current density through the electrolyte are as follows.

\[ I = \frac{E}{R} = \frac{E \sigma}{l} \quad [\text{A}] \quad (3-4) \]
\begin{equation}
  i = \frac{I}{s} = \frac{E}{l} \text{ [A/㎠]} \quad (3-5)
\end{equation}

The removal rate of electropolishing process is predicted theoretically using Faraday's law and the theoretical equation condition is as follows.

1) The eluted atom of metal should be confirmed
2) The metal elution is the only from the atom state caused by the electrochemical reaction
3) The metal elution is the only reaction at the both ends (anode and cathode)

According to the Faraday's law, the necessary quantity of electricity to elute 1 g element which is consist of atomic value \( n \) and atomic weight \( M \) is \( \frac{nF}{M} \) coulomb. Therefore the eluted element quantity \( W_g \) caused by \( I \text{[A]} \) current during \( t \text{[s]} \) time is as follow.

\begin{equation}
  W = \frac{MI}{nF} \text{[g]} \quad (3-6)
\end{equation}

where \( F \) is Faraday constant. When the density of this atom is \( \rho \) the theoretical removal volume \( V_0 \) is as follow.

\begin{equation}
  V_0 = \frac{MI}{nF\rho} \text{ [㎟]} \quad (3-7)
\end{equation}

where \( M/nF\rho \) is specific removal volume \( v_0 \) which eluted volume per unit
quantity of electricity, which differs as the metal type.

The electrochemical equivalent of metal element $k$ is as follow equation.

$$ V_0 = \frac{MIt}{nF\rho} \text{ [mm]} \quad (3-8) $$

When the metal to be machined is an alloy, electrochemical equivalent $k'$ is

$$ \frac{1}{k'} = \sum \left( \frac{w_i}{k_i} \right) \quad (3-9) $$

where $w_i$ is each material ratio of alloy, $k_i$ is an electrochemical equivalent of each metal element.

The eluted quantity and volume can be defined by using a electrochemical equivalent as follow.

$$ W = kIt \text{ [g]} \quad (3-10) $$

$$ V_0 = \frac{kIt}{\rho} \text{ [mm/A.min]} \quad (3-11) $$

But the real removal rate of electropolishing is less than the theoretical value as the various machining condition, environment, material property and etc. So the real removal rate of electropolishing is that multiply theoretical value by current efficiency $\eta$. 

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\[ M = \eta W \quad (3-12) \]
\[ V = \eta V_0 \quad (3-13) \]

\[ \eta = \frac{\text{real removal rate}}{\text{theoretical removal rate}} \quad (3-14) \]

The current efficiency is very closely connected with current density.
Fig. 3-1 Fundamental principal of Electro-Polishing
Fig. 3-2 Simple illustration of polarization curve of Electro-Polishing,
AB: corrosion, dissolution(etching), BC: passive, CD: flated mirror surface(Electro-Polishing), DE: pitting
Fig. 3-3 Electro-Polishing mechanism
3.2 Characteristics of Electrolytic-Deburring

3.2.1 Surface planarization

Fig. 3-3 show the process of levelling the surface. Electropolishing improves surface roughness (Ra) about 50% of metal such as stainless steel, aluminum and etc. The elution by the electrochemical reaction is happened at the prominence(凸) part than the depression(凹) part, so the surface planarization is performed. And as not only the surface roughness but also the tolerance is important, proper parameter value should be selected as the each metal property.[9]

3.2.2 Remove of Hydrogen

In case of being hydrogen on the metal surface there are two serious problem, fatigue fracture and the propagation of bacteria. The hydrogen not only being on the surface but also inside the metal can be removed by the Electrolytic-deburring, so the fatigue fracture is prevented.[9]

3.2.3 Better Corrosion Properties

Electro-deburring gives excellent corrosion resistant characteristics to the workpiece by removing impurities, damaged layers and materials which form a nucleus of corrosion from the workpiece surface.[9]

3.2.4 Remove of Discoloration and Residual Stress

The residual stress and the discoloration on the surface caused by the heat treatment and the welding can be easily removed by the Electrolytic-deburring.[10]
3.2.5 Brilliance of Surface

Electropolishing is known as the excellent machining for the uniformity, brilliance and removal of metal. The Cr multi-layer produced on the surface is very similar the Cr coating layer excepting the adhesive property. So the Cr multi-layer has a strong corrosion property and brilliance property. The planarization surface machined by electropolishing cause a very high brilliance surface reflect the light.
3.3 Mechanism of Electrolytic-Deburring

The mechanism of electro-deburring is not clearly explained yet, but there are four strong hypothesis as follows.[7]

- **Current distribution control theory**
  When the metal is dissolved, the viscous liquid layer is formed on the metal surface and the critical current density is determined as the liquid layer. This liquid layer is filmy at the prominence part, but thick at the depression part. As the current resistant at the prominence part is low but high at the depression part, the prominence part is dissolved faster than the depression part because the positive current is concentrated on the prominence part. As a result the surface planarization is achieved.

- **Acceptor mechanism theory**
  The dissolved metal ion or diffusion layer of ion acceptor which is diffused in the solution to join with metal ion is considered. As this metal ion and the concentration gradient of ion acceptor in the inside of the diffusion layer is large at the prominence part and small at the depression part, the diffusion speed at the prominence part is faster than at the depression part.

- **Local electric cell theory**
  The metal ion gather at the depression part and it conducts as a local cathode. And the local cathode make a local electric cell with a prominence part whose
metal ion concentration is lower relatively. So the anode part, prominence part, is dissolved.

- **Film breakdown theory**
  - Gas polarization effect: The generated gas break the film of the prominence part so it becomes the anode.
  - Surface tension effect: As the surface tension is changed because the current is concentrated on the prominence part, the film is breakdown.

- **Formation and breaking of passivity**
The perfect form of passivity is originated in study of Schonbein and Faraday who observed about chemical passivity of iron in high concentration nitric acid. From the observation, the iron being passivation state after the gas generation and metal elution was protected by acid although the strong reaction force was applied. Faraday express this state as "an oxidized state of the surface". The decrease of nitric acid during the chemical passivity of metal is a accompanying reaction process of cathode from anode passivity process. It is easily proved as electric connecting the iron and platinum which is in very high concentration nitric acid solution.
Fig. 3-4 Characteristic of Voltage-Current of Electro-Polishing; as increase the electric potential and current like AB, it is reached to the B.
$V_p$: the start voltage that metal is ionized

$V_d$: the voltage that the metallic oxide is formed

Fig. 3-5 The metal reaction state as the electrolyte pH and voltage in electropolishing
(a) Dissolution: Water molecules are adsorbed on all the surface. Cations at kink sites A move to solution sites S, to become $M^{2+}_{aq}$.

(b) Passivation: Protons P leave the adsorbed water molecules, leaving $O^{2-}$ ions, and cations at kink sites A and any other sites B move into positions F between the $O^{2-}$ ions, producing a mono layer film of oxide.

Fig. 3-6 The mechanism of metal elution and passivation process in electropolishing
Fig. 3-7 The anode state as the relation of current and voltage in electropolishing
Fig. 3-8 The relation of the anode potential and film thickness
Fig. 3-9 The anode state as the voltage and the ratio of an anion and water
Chapter 4. Electrolytic-Deburring System

4.1 Schematic of System

Fig. 4-1 shows the schematic of the electrolytic-deburring system of medical stent. The electrode and the workpiece is connected to the negative and the positive respectively. The current from the power supply is applied to the electrode and the workpiece. The circulation pump and the filter system to remove the chip due to the repetition of the electrolytic-deburring machining. The chip interrupt the uniform current flow.

The electrolytic-deburring system is consisted of electrode transfer, electrolyte provider, circulation pump, power controller and jig. The length of the stent is several tens ㎜ and the inside diameter is about 10㎜. The electrode gap between the electrode and the stent must be uniform to deburring the all of the area. Therefore in this study, cone shape(□□□□) jig is designed.
Fig. 4-1 Schematic of the Electrolytic-Deburring System
Fig. 4-2 Electrolytic-Deburring System
4.2 Power controller

The power controller is consisted of 'Regulated DC power supply' and 'Micro Computer & Controller'. The voltage, current, machining time is set up at person's disposition. It is possible to select the DC voltage 100V, 150V and the current range is 1~30A, the minimum On time and off time step is 1 \( \mu \text{m} \) respectively. CRT display is built in so it's very convenient to confirm the machining process.

![Power controller system](image)

*Fig. 4-3 Power controller system*
4.3 Electrode for the Stent

The electrode for the stent is depicted in Fig. 4-4. The stent contact with the inner parts of the body so outside and inside should be deburring. Therefore as like Fig. 4-4, $\phi 8 \text{㎜}$ cylinder is built in the center of the cylinder with $\phi 10 \text{㎜}$ inner diameter. So the inside and outside of the stent are machined at the same time.

![Fig. 4-4 Electrode for the Stent](image)
4.4 Jig for the Stent

The jig for the stent is depicted in Fig. 4-5. The center of the cylinder shape jig is machined with φ8 mm or φ9 mm to fix the stent. But this way has a disadvantage. The stent should be deburring all over the area at the same time. But if the stent is deburring with this way, fixing area is not deburring. Therefore more study about the fixing the stent is needed. The jig is fixed to the chuck collet way.

Fig. 4-5 Jig for the Stent
4.5 Up and Down transfer system

Fig. 4-6 shows the up and down transfer system. There are two way to transfer the electrode, macro and micro. (a) is a handling to move the electrode up and down in macro scale and (b) is a micro moving tool that have a 10μm resolution to keep the electrode gap between the stent and the electrode all the part.

Fig. 4-6 Up and down transfer system
4.6 Electrolyte circulation and Filtering system

Fig. 4-7 shows the electrolyte circulation and filtering system. The used electrolyte flow into the filter by the pump located at the bottom of the system. Then the impurities is filtered and the electrolyte flow into the electrolyte tank. The electrode gap is set up about 1 mm so the impurities make the machining effect low. Therefore it is very important to filter the impurities. The PVC pipe that strongly resist to the acid is used to connect the pump and filter. The environment pollution is decreased by this system.

Fig. 4-7 Filtering system
Chapter 5. Experiment and Result

5.1 Preliminary Experiment

Before the experiment with stent, the preliminary experiment was conducted to select the electrolytic-deburring condition for the nitinol material. Fig. 5-1 shows the experiment equipment set up. The nitinol(workpiece) and Cu(electrode) is connected to the anode and cathode respectively. To control the precise electrode gap between the workpiece and electrode, the micro controller with 10\(\mu\text{m}\) resolution to x, y, z direction was used. The power controller provide pulse-voltage rather than DC voltage. The pulse-voltage suppress the hydrogen gas, oxygen gas and heat caused by the reaction of electrochemical. Therefore the stable electrolyte-deburring is possible.

To select the first deburring condition, experiment was conducted with duty factor 0.5 and current density 1~6A/cm\(^2\). The electrolyte-deburring between the current density 1~4A/cm\(^2\), the hydrogen gas was generated and the rough cutting area was to be planarization. But the deburring effect was not shown by much. Above current density 5A/cm\(^2\), the active electrochemical eluted reaction with much hydrogen gas was started. Fig. 5-2 shows the burr size as the machining time. The burr size was observed 300\(\mu\text{m}\) at the first time. After 30 second the size become smaller to 200\(\mu\text{m}\). After 60 second the burr was removed perfectly. Fig. 5-3 shows the planarization of the cutting plane as the machining time. The cutting plane is the M shape at the first. As the machining, the M shape is to be planarization by degrees and it is to be perfect straight line after 360s.
Fig. 5-1 Schematic of the electrolytic-deburring system
Fig. 5-2 Burr size as the machining time
Fig. 5-3 Planarization of the cutting plane as the machining time
Fig. 5-4 shows the electropolishing effect during the electrolytic-deburring. Before the electrolytic-deburring, buffing was conducted with the buffing machine. Surface roughness of the workpiece was 3.07\(\mu m\) at the first time and after buffing it was improved to the 2.94\(\mu m\). Electrolytic-deburring was conducted at 30s intervals. The surface roughness was improved as the machining time and it was 2.77\(\mu m\) after 150s. Fig. 5-5 ~ Fig. 5-7 shows the surface roughness profile as the each machining time.

Fig. 5-4 The electropolishing effect during the electrolytic-deburring
First  Ra: 3.07 μm  Rmax: 23.1 μm

Buffing  Ra: 2.94 μm  Rmax: 19.4 μm

30s  Ra: 2.87 μm  Rmax: 20.1 μm

Fig. 5-5 Surface roughness(Ra): Machining time First, Buffing and 30s
Fig. 5-6 Surface roughness (Ra): Machining time 60s, 90s and 120s
Fig. 5-7 Surface roughness (Ra): Machining time 150s

150s  Ra: 2.40 μm  Rmax: 23.1 μm
5.2 Experiments design

Experiments design is used to analyze and to make an experiment. The Experiments design is defined as the statistical method to design and to analyze the given experiment using minimum experiment number. This experiments design is used for the many ways such as manufacturing, machining, food, quality as well as service. Especially, it is used for the non-traditional machining field which is particular and required much expensive. In this study, the effect of the electropolishing is observed through the preliminary experiment and the proper parameters are selected. And the experiment is performed and analyzed using the RMS and surface roughness of the nitinol as the machining parameter is observed.

5.2.1 Selection of machining parameters

Surface roughness after the experiment is measured as changing of the current density, machining time and electrode gap during consist of the electrolyte, material of the electrode, machining temperature is set up as the fixing condition. The fixing condition and the machining parameters are depicted in Table 5-1 and Table 5-2 respectively.

5.2.2 RMS

RMS is defined as the statistical analysis method for the response surface made by response change when the several explanation parameter influence compositively the certain response parameter. The response parameter has a certain response surface as the explanation change and it is the purpose of the RMA to describe the response surface as the function of analytical shape. The main
The purpose of the response analysis is to find an optimal value of the explanation parameter making the result best or to predict the result of the optional parameter. The function between the explanation parameter and a dependent variable is depicted as follows.

\[ \eta = f(s_1, s_2, \cdots, s_k) \quad (5-1) \]

The new dependent variable is defined as changing the explanation parameter linearly to assume a regression shape as the response function. The 1st and 2nd regression is depicted as follows.

\[ \eta = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k \quad (5-2) \]

\[ \eta = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i\leq j}^{k} \beta_{ij} x_i x_j \quad (5-3) \]

In this study, the 2nd regression shape is thought proper so the proper response surface is expressed due to the method of least squares setting the \( \eta \) value.

\[ \hat{\eta} = \hat{\beta}_0 + \sum_{i=1}^{k} \hat{\beta}_i x_i + \sum_{i\leq j}^{k} \hat{\beta}_{ij} x_i x_j \quad (5-4) \]

\( \hat{\eta} \) is an estimated volume of \( \eta \) and \( \hat{\beta}_0, \hat{\beta}_i, \hat{\beta}_{ij} \) is depicted an estimated volume of least squares respectively. The regression coefficient \( \hat{\beta}_0, \hat{\beta}_i, \hat{\beta}_{ij} \) is presumed as
follows.

\[
[\beta] = ([X']^[X])^{-1}[X']^y \quad (5-5)
\]

\([X]\) is the matrix being consist of each experiment condition and \([Y]\) is the matrix being consist of experiment value. How this relation of function is valid is estimated using the coefficient of determination found from sum of square and sum of regression square of total deviation.

### 5.2.3 Machining condition and experiments design

The machining parameters are three value and each maximum and minimum value is depicted in Table 5-2. The experiments is designed using the CCD(Central Composite Design) of RMS. The experiments is performed 18 times due to the this experiments design and 1 is selected as the value of the axial points \(\alpha\) Matlab program is used to derive the regression analysis formula and to express the graph for the a dependent variable as the each machining parameters.

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition of electrolyte</td>
<td>H(_3)PO(_4), H(_2)SO(_4), Distilled water(5:3:2)</td>
</tr>
<tr>
<td>Workpiece</td>
<td>Nitinol</td>
</tr>
<tr>
<td>Electrode</td>
<td>Copper</td>
</tr>
<tr>
<td>Temperature</td>
<td>Normal temperature</td>
</tr>
</tbody>
</table>
### Table 5-2 Design scheme of process parameters and their levels

<table>
<thead>
<tr>
<th>Factor symbol</th>
<th>Parameter</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Current density (A/cm²)</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>B</td>
<td>Polishing time (sec)</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90</td>
</tr>
<tr>
<td>C</td>
<td>Electrode gap (mm)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
</tr>
</tbody>
</table>

### Table 5-3 Design of experimental matrix and linear transformation of each parameter and observed values

<table>
<thead>
<tr>
<th>Exp. No.</th>
<th>Process parameters</th>
<th>Linear transformation</th>
<th>Observed values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Current density A/cm², A</td>
<td>Polishing time sec, B</td>
<td>Electrode gap mm, C</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>60</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
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<td>120</td>
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<td>9</td>
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<td>1</td>
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<td>9</td>
<td>60</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>9</td>
<td>120</td>
<td>1</td>
</tr>
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<td>8</td>
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</tr>
<tr>
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</tr>
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</tr>
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</tr>
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<tr>
<td>18</td>
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</table>

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### Table 5-4 ANOVA table for Surface roughness

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of squares</th>
<th>Degrees of freedom</th>
<th>Mean square</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>0.5423</td>
<td>9</td>
<td>0.06025556</td>
</tr>
<tr>
<td>Residual</td>
<td>0.0817</td>
<td>8</td>
<td>0.0102125</td>
</tr>
<tr>
<td>R^2</td>
<td>0.869070513</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5.2.4 Experiment result and analysis

This experiment is performed as the central composite design which is consist of 3 factors and 3 levels. The surface roughness from this experiment result is measured and the regression formula is acquired. Therefore it is possible to predict the surface roughness. Table 5-3 shows the machining parameter of each experiment, linear transformation and experiment result. Each factor level is set up as minimum, maximum and axial point and they are transformed as -1, 0, 1 respectively. The surface roughness is a average of the measured value. The 2nd regression analysis formula derived from the above statements is as follows.

\[
\hat{y} = 1.2311 -0.0400x_1 + 0.0140x_2 \\
+ 0.1320x_3 + 0.1004x_1^2 + 0.0004x_2^2 \\
- 0.1496x_3^2 - 0.1763x_1x_2 + 0.0262x_1x_3 \\
-0.0563x_2x_3 \quad (5-6)
\]

Above regression analysis formula is derived from each parameter is linearly transformed. The regression analysis formula which is derived from that linear transformation is replaced original value is as follows.

\[
\hat{y} = 0.0479 + 0.0116A + 0.0159B \\
+ 0.8469C + 0.0112A^2 + 0.0000B^2 \\
-0.1496C^2 -0.0020AB + 0.0087AC \\
-0.0019BC \quad (5-7)
\]

The analysis of variance table for the above regression analysis formula is
depicted in Table 5-4. The coefficient of determination ($R^2$) of this experiment is 0.87. As the correlation between the explanation variable and dependent variable is increase, the $R^2$ is closed to the 1. The regression analysis formula of this experiment has a 86% confidence rate.

The stationary point $X_0$ to perform the canonical analysis is as follows.

$$X_0 = [-0.0752, -0.2411, 0.4800]$$  \hspace{1cm} (5-8)

The estimation value of the surface roughness from above is 1.26 $\mu$m. The current density is 5.8A/cm², machining time is 83s, electrode gap is 2.5 mm. The canonical analysis derived from this stationary point is as follows.

$$f_0 = 1.2626 - 0.1548\omega_1^2 - 0.0480\omega_2^2 + 0.1539\omega_3^2$$  \hspace{1cm} (5-9)

The stationary point is a saddle point (not maximum and minimum point) because the characteristics value is consist of positive and negative value. Therefore the result shows that the surface roughness has a direction of increase and decrease.

The graph is described for the two variable during the one variable is fixing. Fig. 5-8(a) shows the surface roughness graph for the current density and machining time. As the current density is high and machining time is long, the surface roughness is better. The estimation value of surface roughness from Fig. 5-8(a) is 1.13 $\mu$m when the current density is 9A/cm² and machining time is 120s.

Fig.5-8(b) shows the surface roughness graph for the current density and electrode gap. As the electrode gap is decreased, the surface roughness is better all over
the range. The estimation value of surface roughness from Fig. 5-8(b) is 0.98\(\mu m\) when the current density is 6.9A/cm\(^2\) and the electrode gap is 1mm.

Fig. 5-8(c) shows the surface roughness graph for the machining time and electrode gap. Like the Fig. 5-8(b) as the electrode gap is decreased, the surface roughness is better. The estimation value of surface roughness from Fig. 5-8(c) is 0.88\(\mu m\) when the machining time is 60s and the electrode gap is 1mm.
Fig. 5-8(a) Effect of current density and polishing time for the surface roughness
Fig. 5-8(b) Effect of current density and electrode gap for the surface roughness
Fig. 5-8(c) Effect of polishing time and electrode gap for surface roughness
5.3 Experiments

From the experiments design, the optimal electropolishing condition for the Nitinol material is when the machining time is 60s and electrode gap is 1㎜. So the experiment is performed as change the current 1A and 3A when the machining time and the electrode gap is fixed 60s and 1㎜ respectively.

The experiment condition is as follow. The current is 1, 3, 5A, machining time is 60s, and the electrolyte is consisted of phosphoric acid, sulphuric acid and DI water. The pulse on-off time is 50μs and 50μs respectively and the electrode gap is 1㎜.

<table>
<thead>
<tr>
<th>Table. 5-5 Experiment Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
</tr>
<tr>
<td>Machining Time</td>
</tr>
<tr>
<td>Electrolyte</td>
</tr>
<tr>
<td>Pulse On-Off time</td>
</tr>
<tr>
<td>Electrode gap</td>
</tr>
<tr>
<td>Workpiece</td>
</tr>
</tbody>
</table>

The stent and the electrode is set up like Fig. 5-9 and fill up the electrolyte. Then the voltage is applied. Many bubble is made around the stent and the electrode. Fig. 5-10 shows the machining state.
Fig. 5-9 Stent insertion into the electrode

Fig. 5-10 The state of the machining
Fig. 5-11 shows the nitinol stent after the laser cutting. The surface is very rough and the edge area is very sharp. Fig. 5-12 is the enlarged photo. The burr at the edge is obviously found. The rough and sharp surface would injure the inner part of the body so it should be removed and polished. Fig. 5-13 shows the stent after electrolytic-deburring with current 1A. It seems that the sharp burr at the edge is removed and the surface roughness is improved. But it need that the edge should be more rounded. So the experiment is performed with 3A current. The Fig. 5-14 shows the result of the experiment. It is obvious that the edge is rounded as compared with the experiment with 1A current. But there are some problem like as Fig. 5-15. As the current is increased, the current density is concentrated on the part of the connect part of the stent wire. So the connect part is too much machined and the shape is very irregular. To solve this problem, the stent design is changed. Fig. 5-16 shows the stent after the design is changed. To prevent the current concentration to the connected part, the connected part is machined concave shape. The new design stent is deburring with 1A. Fig. 5-17 show the stent after electrolytic-deburring with 1A current. The surface brilliance is improved as compared with the before deburring. But the edge part is needed more rounded. Fig. 5-18 shows the electrolytic-deburring with 3A current. The surface brilliance is good and the edge part is very smooth. And in contrast with the original stent design, the surface is not irregular.
Fig. 5-11 Stent after the laser cutting: the surface is very rough and there is a much burr at the edge.
Fig. 5-12 There is a sharp burr at the edge after the laser cutting
Fig. 5-13 Stent After the electrolytic-deburring with 1A
Fig. 5-14 The edge part is more rounded with 3A than 1A
Fig. 5-15 Irregular surface after electrolytic-deburring with 3A current because the too much current density concentration to the connected part
Fig. 5-16 Before(a) and after(b) change the stent design. The connected part is machined concave shape.
Fig. 5-17 Before the electrolytic-deburring (a) and after electrolytic-deburring with 1A
Fig. 5-18 The stent after the electrolytic-deburring with 3A current
Fig. 5-19 The stent after the electrolytic-deburring with 3A current. The surface brilliance is improved and the edge part is very smooth as compared with Fig. 6-8.
Chapter 6. Conclusion

In this study, the medical stent electrolytic-deburring system is developed and the experiment is performed. Through the preliminary experiment and the experiments design, the optimal machining condition is selected about nitinol material. Basis of this preliminary experiment, the system is designed and developed. Machining parameters are very important in electrolytic-deburring and results are different according to each parameters.

First, the electrolytic-deburring is not performed effectively above the 1\,\text{mm} electrode gap. On the other hand below the 1\,\text{mm} electrode gap, the current density is concentrated on the connection part so the part is too much machined and it is difficult to keep the electrode gap.

Second, below the 3A current the electrolysis reaction is not happened well. Therefore the electrolytic-deburring is not conducted. And above the 3A, there is a too much eruption of the stent so the surface of the stent is not good.

Third, from a result of the experiments design, the optimal electro-deburring condition is that when the machining time is 60s and electrode gap is 1\,\text{mm}. The current density didn't affect to the electro-deburring as the above two variables.

Forth, when the experiment is performed with current 1A, the electro-deburring
is not performed effectively and with current 3A the electro-deburring is performed effectively. But the current density is concentrated on the connection part so the part is too much machined and the surface is irregular. Therefore to solve this problem the stent design is changed. After change the shape, the irregular machining is ration is not found.
본 논문에서는 의료용 니티놀 스텐트의 전해 디버링을 위한 시스템 개발 및 디버링에 관한 연구를 하였다. 스텐트는 인체 내강과 직접적으로 접하기 때문에 표면에 있는 미세 버 제거 및 표면 폴리싱이 반드시 필요하다. 현재 개발되고 있는 스�滕트 제품에 적합한 시스템을 개발하였으며, 주요 구성요소로는 스텴트 지그, 전극, 전해액 필터 시스템이 있다. 본 실험에 앞서 최근 스텴트 재질로 많이 사용되고 있는 니티놀 재질에 대한 전해디버링 실험을 하였다. 니티놀은 형상기억의 성질이 있기 때문에 최근 스텴트 뿐만 아니라 많은 분야에서 사용되고 있다. 그리고 최적의 가공 조건을 도출하기 위해서 실험계획법을 이용하였다. 실험계획법을 통해 최적의 가공 조건을 도출하여 실제 양산되고 있는 스텴트에 적용하였다.
Reference


감사의 글

2년이라는 결코 짧지 않은 시간을 보내지 않은 많은 아쉬움이 남습니다. 좀 더 열심히 잘했으면 하는 마음입니다. 하지만 많이 부족함에도 2년의 결실이 담겨있는 논문이기에 소중한 것 같습니다.

먼저 부족한 자를 이끌어 주시고 사용하시는 하나님께 감사를 드립니다. 하나님께서 저에게 주신 비전을 이루기 위해서 앞으로도 한 걸음 한 걸음 전진하는 삶을 살겠습니다.

사랑하는 아버지 어머니에게 감사를 드립니다. 자랑스러운 아들인 되도록 노력하십시오. 못된 동생임에도 항상 챙겨주고 관심을 가져준 형에게 감사드립니다.

저에게 배움의 길을 주신 이윤상 지도 교수님께 깊은 감사를 드립니다. 지난 2년여 동안 세심한 지도와 용기를 주신 감사를 드립니다. 앞으로 교수님께서 항상 강조하셨던 노력하는 모습 보이도록 저에게 주어진 모든 일에 열심히 최선을 다하겠습니다.

대학원 생활을 즐겁게 지낼 수 있도록 도와준 연구실 형들과 동기들에게 감사드립니다. 항상 따뜻한 마음으로 연구실을 돌봐주시고 여러분이 있음을 때마다 없어서도 주신 영원한 대장 승엽이 형과 많은 사회경험을 통해서 도움을 주신 종구 형과 신현정 박사님께도 감사를 드립니다. 저에게 새로운 도전을 주시고 많은 조언을 주신 영재형, 입학동기로서 옆에서 항상 도움과 웃
음을 나눈 챔피온 정훈이형, 때지 진용이형에게도 감사를 드립니다. 연구실의 살림꾼이자 브레인 정현이형, 항상 번뜩이는 아이디어와 유쾌한 웃음을 가 지고 있는 정택이형, 미모와 지성을 갖춘 아름다운 아가씨 민정이형에게도 감 사를 드립니다. 그리고 UPNS를 졸업한 모든 선배님들께도 감사를 드립니다. 고체생산 파트의 일영이형, 경호형, 병철이형, 진화형, 동우형, 건희형, 봉철이형, 세진이형, 동혁이형, 노훈이형, 정원이형에게도 감사를 드립니다.

마지막으로 나의 사랑하는 공동체 젊은씨앗과 영원한 멘토 최지훈 목사님께 깊은 감사를 드립니다.

2006년 7월 19일 11:04PM
김 원묵 드림