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Development of a New Internal Finishing of Tube by Magnetic Abrasive Finishing Process Combined with Electrochemical Machining

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Abstract: The research proposes a new internal surface magnetic abrasive finishing (MAF) process, which compounded with electrochemical machining (ECM) to decrease machining time. The electrochemical process changes the morphology of the aluminum tube internal surface, producing an oxidation film. Then, we removed the film by magnetic abrasive finishing, results in minimized surface roughness in a significantly reduced processing time when compared to the conventional MAF. In this research, a new experimental set up with a tool that capable of magnetic abrasive finishing and electrochemical finishing was designed and developed to study the machining feasibility. The newly developed finishing method demonstrated simultaneous process of aluminum oxide film formation by ECM and its removal by MAF. This process plays a significant role in preventing the deepening of the pit during ECM and speed up the planarization. The method was developed step by step; firstly, ECM and MAF were conducted in two separate processes. In the second experiment, we modified the finishing conditions to facilitate one-stage finishing method. An investigation of the finishing surface is focusing on the pit size that formed by ECM. The pit size indicated the residue of oxide film because it is a part of the oxidation film construction. Pits morphology changes were observed for certain finishing time to determine the minimum finishing time for its removal. Surface roughness and SEM photograph of the finishing surface were recorded and studied.

Keywords: Magnetic Abrasive Finishing, Electrochemical Machining, Internal Surface Finishing, Surface Roughness, Finishing Characteristic, Aluminum Tube Finishing

1. Introduction

The utilization of clean tubes or sanitary tubes in the field of semiconductor, chemicals, biotechnology, etc. fields is essential since the smooth surface prevents accumulation of dirt or oils in fine grooves that exists on rough metal surfaces. In a highly pressured container, dirt accumulations could cause corrosion and leading to burst and explosions [1]. In the food sector, rough surface in food tanks promotes microbial growth [2]. Due to expanding business in these fields, the recent trend shows that demand for clean tube has significantly increased. Moreover, for tube length more than 2 meters, internal finishing using machines has various mechanical constraints and finishing process is time-consuming. Method to polish tube internal surface using magnetic slurry for a thin tube was proposed in 1999 for thickness less than 5mm [3], [4]. This method works by placing a slurry that consist iron powder, white alumina and polishing agent in the tube with the present of magnetic field from the magnetic poles positioned outside of the tube. As the poles and tube rotate in the opposite direction, the movement results in finishing mechanism to the tube internal wall from the magnetic force that reacts on the slurry to the tube. The slurry moves with agitation in the tube, and this movement causes abrasives mixing while the process takes place, replacing abrasives that contacted with the surface constantly along the process. The mechanism prolonged the slurry life. However, as the tube thickness increases, the distance between poles and magnetic slurry also increase, results in the magnetic force to drop significantly. Magnetic machining jig was proposed for finishing of thick tubes (thickness 5~30mm) and has been successful in polishing thick tubes internal surface [5]–[7]. The magnetic machining jig constructed with magnet and yoke is positioned in the tube so that it creates a closed magnetic circuit that gathers magnetic flux into the circuit. This construction demonstrated more than ten times stronger machining force than without it [8]. Detailed study regarding the machining jig development and characteristics was performed for flat surface finishing and internal finishing in tubes. In this method, magnetic jig moves synchronically with the external poles and at the same time polish tube internal surface with magnetically adhered slurry at the magnet side of the jig. Compared to other metal, aluminum is softer in physical characteristic, has a lower melting point and difficult to polish. Therefore, it requires specific conditions to be polished to high surface finish. The finishing of the aluminum tube using MAF was proposed, and optimum finishing conditions was explained [9].

On the other hand, electrochemical machining is well known due to its short finishing time and high surface finishing capability for metals such as SUS304 [10], [11]. Electrochemical finishing for aluminum causes pits in most cases [12], [13]. The studies regarding pit reduction by vibration methods were reported in several studies [14], [15]. Meanwhile, El-Taweed has integrated electrochemical turning process and magnetic abrasive finishing for finishing of the aluminum rod external surface. However, the surface finishing is still relatively low [16]. Liu had studied the development of processing aluminum using electrochemical magnetic abrasive finishing for flat surface had clarified the finishing characteristic of the process for a variety of conditions [17]. Nevertheless, the study lacking focus on the pit formed by electrochemical machining that may have directly affected the surface roughness.

In this research, we proposed the magnetic abrasive finishing (MAF) combined with electrochemical machining (ECM) which is also known as electrochemical magnetic abrasive finishing (EMAF) for finishing of tube internal surface. The electrochemical process modifies the uneven surface morphology by creating oxidation film. Afterward, the MAF plays an important role in removing the film and finishing the surface. MAF quickly removes the oxidation film because of the porous aluminum oxide itself built of [18]. In the final process, with the two processes combined, results in a significant reduction in total processing time compared to the conventional MAF. The oxidation film has pits on it that is visible through SEM. We conducted an investigation on the finishing surface morphology for observations of removal of pits by MAF in the final stage to ensure achieving a minimized surface roughness. Observation of surface through SEM photographs and measurement of surface roughness was done to evaluate the morphology changes. Average surface roughness, R_a was measured using contact-type surface roughness (Surftest SV-624-3D, Mitutoyo).

2. Processing Principle

The ECM takes place in the presence of an electrolyte and current supply between workpiece (anode) and combination machining tool (cathode), which develops aluminum oxide on the workpiece internal surface. The electrochemical equation for both anode and cathode are shown as the following: [19].

$$\text{Anode: } 2OH^- \rightarrow H_2O\ 1/2O_2 + 2e^- \quad (1)$$

$$\text{Cathode: } H^+ + e^- \rightarrow 1/2H_2 \quad (2)$$

From (1), we understand that the oxygen gas is released at the anode. The oxygen reacts directly with aluminum on the surface to form aluminum oxide film. This reaction creates pit on the surface. At the same time of the ECM, MAF takes place to remove the aluminum oxide film. The slurry consists of iron powder, white alumina and polishing agent, become magnetized on the magnet side of the combination machining tool to form magnetized particles. The machining effects caused by white alumina abrasives that move with magnetic particles finishes the tube internal surface through this process.

The formation of oxidation film by ECM and removal by MAF is on-going at the same time. After a particular period, the ECM process is stopped, but the continuity of MAF is designed to remove the residual of the oxidation film. The porous and soft structure of the oxidation film accelerates the process when compared to conventional MAF process that works on the hard aluminum surface.

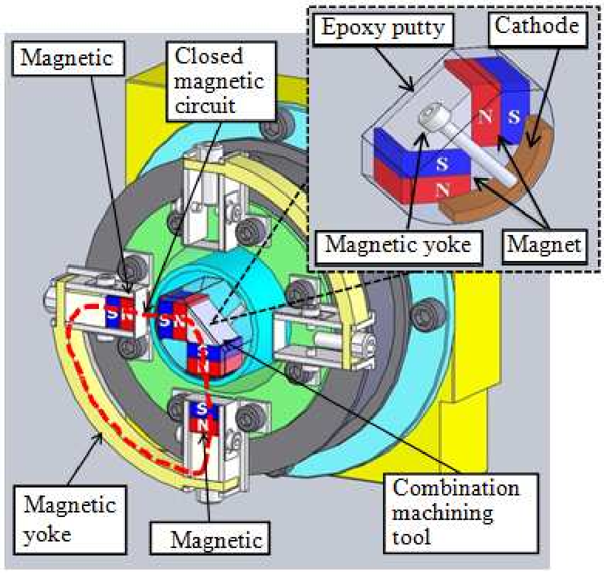


Figure 1. *Schematic of processing principle.*

Figure 1 shows the schematic of processing principle of magnetic abrasive finishing with combined electrochemical finishing in 3D model and machining tool structure. The machining tool has two functions; magnetic abrasive finishing and electrochemical finishing. Hence, we called it combination machining tool. The tool`s N-S poles, external magnetic poles and magnetic yoke are positioned inside the tube with the N-S-N-S sequence to create a closed magnetic circuit as shown in the figure. This construction creates a strong magnetic force, which push towards tube internal surface direction. When the external magnetic poles are rotated, the combination machining tool synchronically rotates with the poles. At the same time, it pushes toward the internal surface. The strong magnetic force is essential for the finishing force, which works in the tangential direction to the tube surface. Meanwhile, the workpiece is also rotated in the opposite rotation of the external poles direction, and stroke movement is applied by a crank mechanism that connected to the chuck.

3. Experimental Method and Conditions

Figure 2 shows the photograph of the experimental setup. The workpiece is fixed to the chuck and the other end to a supporter. Rotation is applied to the workpiece by turning the chuck that is connected with a spindle and pulley system to motor A. Motor B applies another rotation of opposite direction to the external magnetic poles. The stroke movement at the workpiece length direction is applied by using a crank mechanism controlled by motor C. The combination machining tool is wrapped with a polyester cloth to prevent scratches to the workpiece. The tool is magnetically adhered with the slurry and positioned in the tube accordingly.

Electrolyte sodium nitrate was pumped from the tank and flows to the tool so that the tool-tube gap fills with it. The ECM starts when the current is supplied to the anode (workpiece) and cathode (tool) by a direct current power supply. The workpiece was ultrasonically washed before and after the process with ethanol, air-dried and measured its weight. Surface contact-type surface roughness was used to measure the average roughness at three places distanced 120 degrees each.

Figure 3 shows the SEM images of the aluminum oxide structure from a study of aluminum oxide growth and characterization. In order to view aluminum oxide film thickness by the SEM photograph, it was done using aluminum purity 99.99% that was produced using magnetron sputtering [20]. However, for the current research, we are using industrial standard aluminum tube A6063 that has the purity of 97.5%. Therefore, the method to observe the film thickness is not suitable because the significant line between aluminum and aluminum oxide film could not be seen. We have decided to observe the pit structures as a parameter to evaluate the surface morphology, additional to the surface roughness measurement using contact-type surface roughness machine.

3.1. Magnetic Abrasive Finishing (MAF)

The conventional MAF process was conducted for comparison. Table 1 shows the detailed experimental conditions with finishing time 5,10,15,20,25,30,35 and 40 minutes. For this experiment, no direct current power supply or electrolyte was used as it only involves MAF. The conditions were similar to previous research conducted for aluminum tube finishing using MAF. The use of bigger size iron particles such as 330 µm causes scratches on the finishing surface. Therefore, the size 149 µm was used [9].

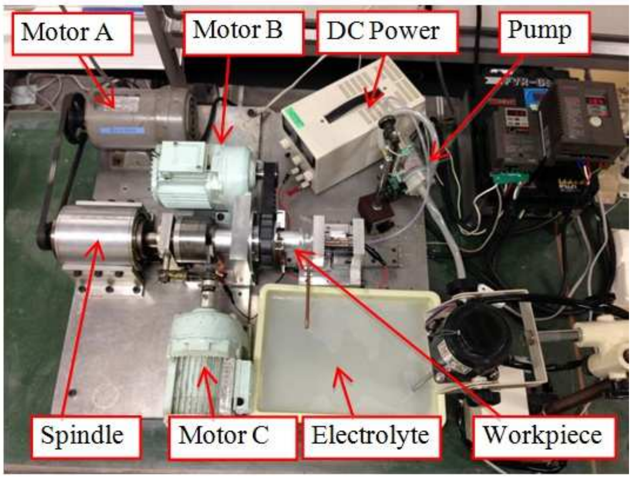


Figure 2. *Photograph of experimental setup.*

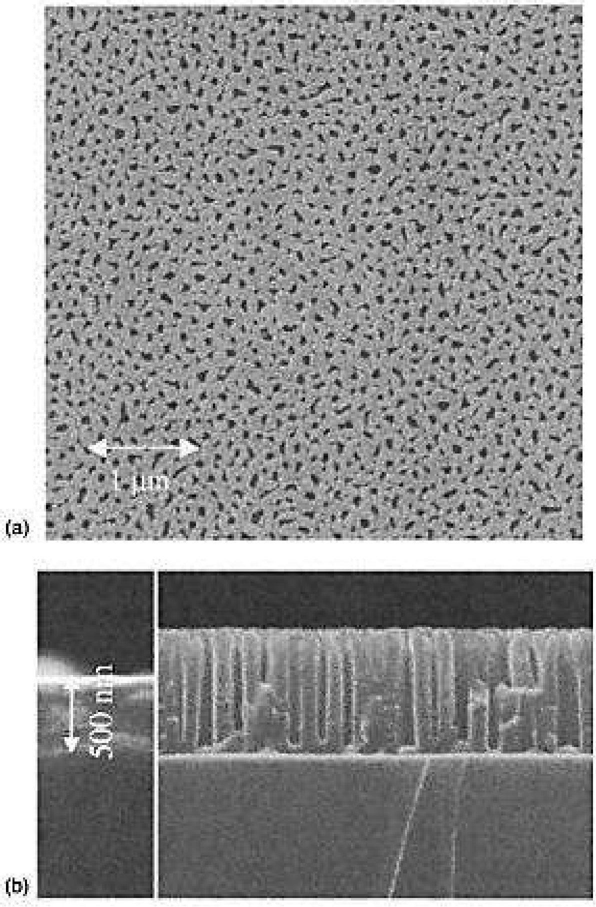


Figure 3. *SEM images (a) looking down on the surface of the porous aluminum oxide and (b) side profiles of the aluminum and the porous aluminum oxide (the expansion upon conversion from the aluminum to the oxide can be seen) [20].*

3.2. Two-Stages Finishing

The process was conducted in two-stages; the ECM followed by the MAF separately. The experiment was conducted in particular processing time combination for both processes to determine the suitable amount of time needed for each process by observing the conditions of oxide film accumulated. Table 2 shows the details experimental conditions for electrochemical finishing. The electrolyte used was sodium nitrate 20% flowed at 30 ml/min by adjusting a flow meter that connected to the pump. Electrical current is set to fix at 0.5 A from the direct current power supply. The machining time for electrochemical finishing was set at 3, 4 and 5 minutes. The combination machining tool was wrapped in a polyester cloth to prevent from scratching the tube. In this stage, no abrasive slurry was used as it involves only ECM. External poles rotation speed was set at 50 rpm with no workpiece rotation. After the process ended, the workpiece is ultrasonically washed in ethanol and measured its weight.

In the second stage, the magnetic abrasive finishing was performed with finishing conditions similar as shown in Table 1 except for the finishing time. It was conducted for 3,4,5, and 6 minutes for certain conditions. The slurry mixture was magnetically adhered on the magnet side on the combination machining tool and positioned in the tube. After the process, the workpiece was ultrasonically washed in ethanol, air-dried and measured its weight.

The finishing time combination was fixed 5 minutes for ECM followed with 5, 4 and 3 minutes of MAF. Next, it was changed 4, 3 and 2 minutes for ECM followed by a fixed 5 minutes of MAF. Surface roughness was measured, and observation on the surface finishing was made under SEM to study the pit size and morphology. This method allow us to know how long the processing time needed for ECM to reduce initial hairlines efficiently and produce the aluminum oxide film, and how long does it takes for MAF to remove the pit morphology and achieve a high finish surface.

Table 1. *Conventional MAF finishing conditions.*

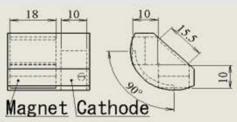
Workpiece	**Aluminum tube A6063 (Ø40xØ36x150 mm)**
Machining tool	Ne-Fe-B rare earth permanent magnet 10x12x18 mm 
Magnetic abrasive mixture	Iron particle 3.5 g (mean diameter 149 μm); WA #10000 0.5 g; Water soluble polishing liquid 2.5 ml
Finishing time	5,10,15,20,25,30,35,40 min
Pole-tube gap	8 mm
Workpiece rotation speed	200 rpm
Poles rotation speed	50 rpm
Stroke	5 mm/s

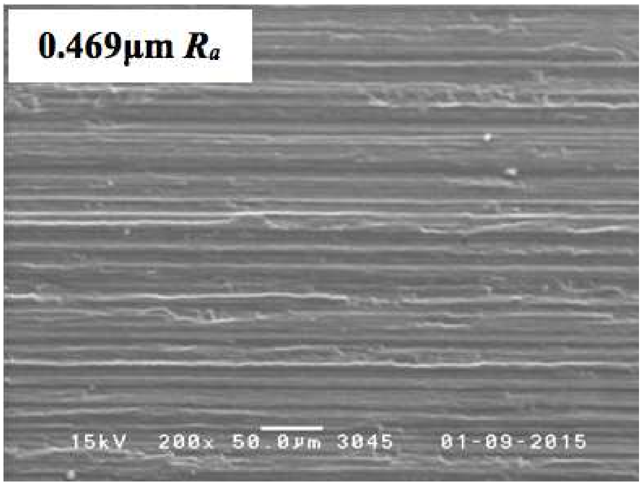
Table 2. *ECM finishing conditions.*

Electrode-tube gap	**1 mm**
Electrolyte	$NaNO_3$ 20% aqueous
Electrolyte amount	30 ml/min
Current density	0.0025 A/mm^2
Poles rotation speed	50 rpm
Finishing time	3,4,5 min

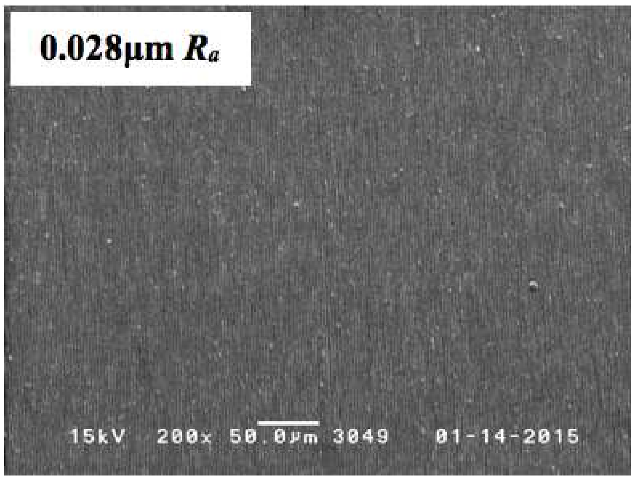
3.3. One-Stage Finishing

For the one-stage finishing method, the process was conducted in one step simultaneously for ECM and MAF. Thus, additional to the quick removal of porous oxidation film, it further cuts processing time. In this method, the combination machining tool was wetted with the 2.0 ml of electrolyte onto the polyester cloth that is used to wrap it. Then, the slurry was magnetically adhered on the magnet side of the tool and positioned in the tube accordingly. The slurry composition is same for MAF as shown in Table 1. Finishing processes were conducted for 8, 9, 10, 11 and 12 minutes of which during that period, the first 2 minutes were allocated for ECM and MAF simultaneously. After 2 minutes, the current supply was shut off to stop the ECM. However, the process continues for MAF for the purpose of resurfacing the aluminum oxide film and removes the pit structures. Similarly, the workpiece is ultrasonically washed, air-dried and measure roughness and weight.

4. Experimental Results and Discussion



(a) Before finishing.



(b) After finishing 40 minutes.

Figure 4. *Surface photograph before and after finishing observed under Scanning Electron Microscope (SEM) (a) before and(b) after finishing.*

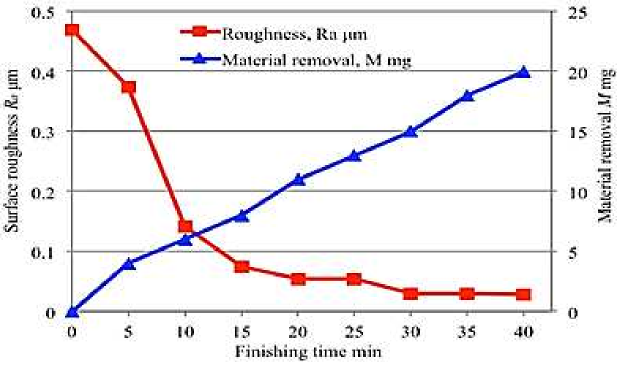
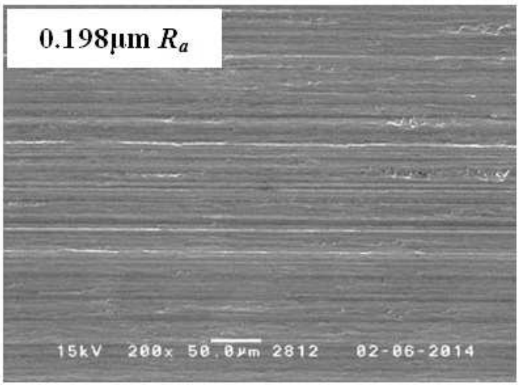
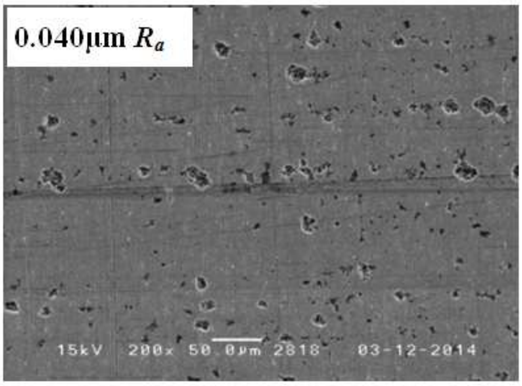


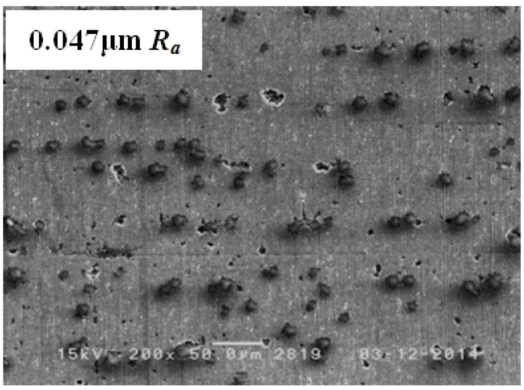
Figure 5. *The change of surface roughness and material removal weight against the finishing time.*



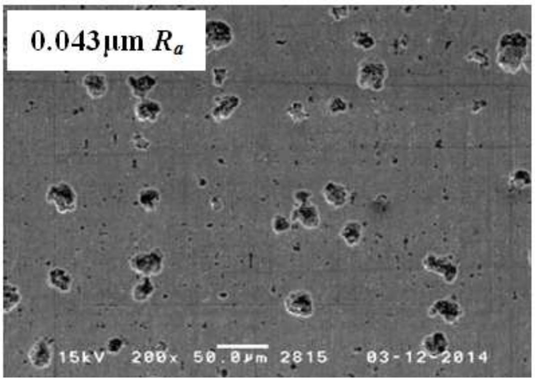
(a) Before finishing.



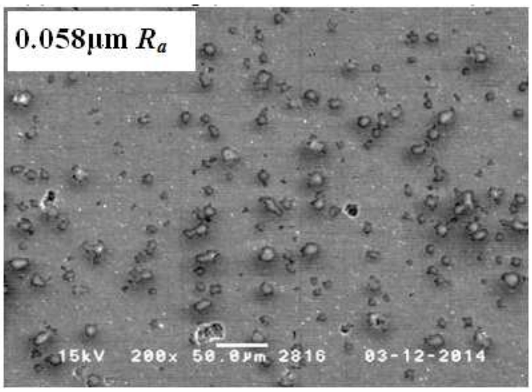
(b) After finishing (5 min ECM+ 5 min MAF).



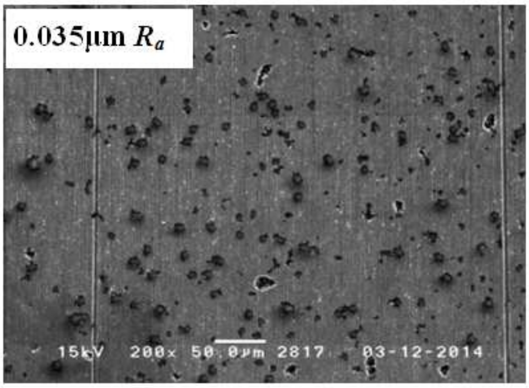
(c) After finishing (5 min ECM+ 4 min MAF).



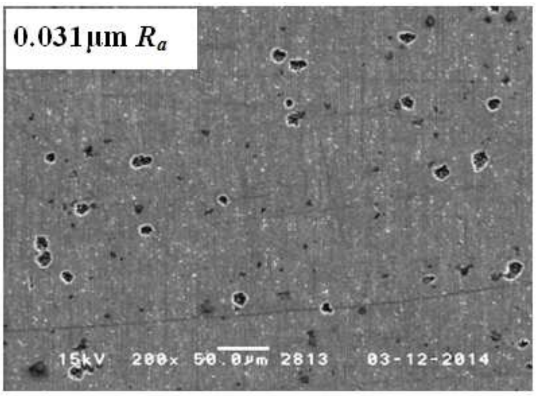
(d) After finishing (5 min ECM+ 3 min MAF).



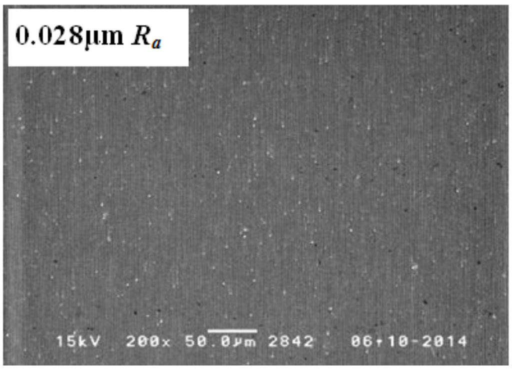
(e) After finishing (4 min ECM+ 5 min MAF).



(f) After finishing (3 min ECM+ 5 min MAF).



(g) After finishing (2 min ECM+ 5 min MAF)



(h) After finishing (2 min ECM+ 6 min MAF).

Figure 6. *Surface photograph before and after finishing observed under Scanning Electron Microscope (SEM) with different finishing time combinations for ECM and MAF separately.*

Aluminum A6063 is softer compared to SUS304. It has Vickers hardness of 70 HV compared to the SUS304, which has 200 HV. The aluminum tube is made by extrusion process that results in hairlines formation on its internal and external surfaces. This internal surface has an initial average roughness that varies ranges from 0.2 to 0.7 µm R_a.

4.1. The conventional MAF

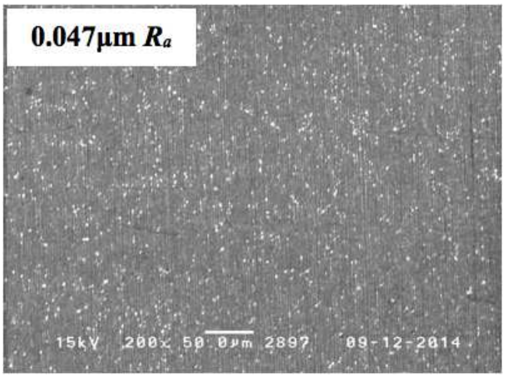
Figure 4(a) shows SEM photograph of the surface before finishing. The initial hairline was seen clearly before the process. Figure 4(b) shows the photograph after processing; the hairlines were removed, and surface roughness measured 0.028 µm R_a. Figure 5 shows the change of surface roughness and material removal against finishing time. The material removal shows constant removal pattern due to the usage of one size iron particle 149 µm through the process for comparison purpose. The surface was gradually leveled and finally it took 30 minutes to achieve surface roughness 0.028 µm R_a.

4.2. Two-Stages Finishing Method

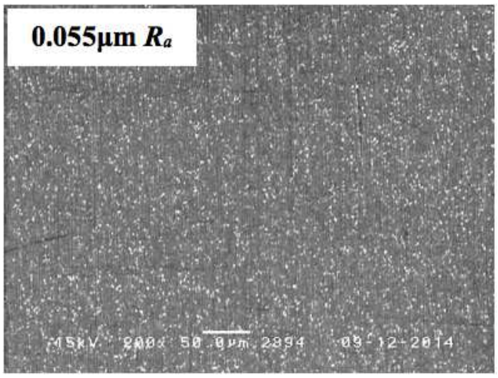
In the first process which is the electrochemical process, the uneven surface undergone a planarization that creates oxidation film on the finishing surface. Figure 6 shows the surface photograph under SEM before and after finishing for different finishing time combination of ECM and MAF. From the observation through SEM, small holes or pit that resulted from etching during the ECM process could be seen. These small holes are part of the oxidation film. The holes diameter is approximately 10 to 20 µm varies depend on the depth. As the removal of oxidation film progress, the size of the pit reduced and gradually diminished as more oxidation film were removed. Figure 6(b) shows that pit still exist with equal processing time for ECM and MAF and even bigger size for shorter MAF time in Figure 6(c) and 6(d). This evident means more MAF time is needed to remove the pit structures. In Figure 6(e) ~ 6(g) we could observed that pit size gradually reduce in the reduction of ECM finishing time. Finally, in Figure 6(h) the pit was completely unseen for the processing time combination. Comparison with MAF process shows that the current method reached a similar level of average surface roughness 0.028 µm R_a within 8 minutes finishing time, compared to the conventional method that took 30 minutes for similar level of surface roughness.

4.3. One-Stage Finishing Method

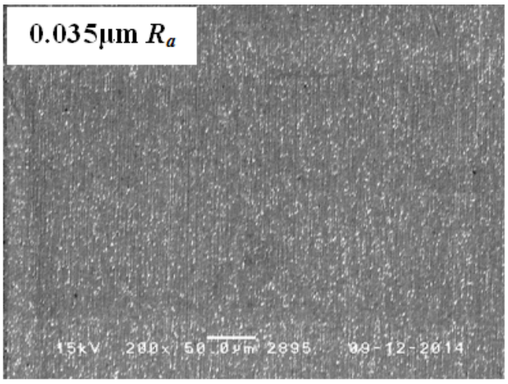
In the one-stage finishing method, the two finishing process were conducted simultaneously in order to reduce the total finishing time. Oxidation film was formed and at the same time being removed for the first two minutes of processing time. However, oxidation film was produced at a faster pace than removal by MAF. As a result, at the point the ECM process ends, an extra processing time of MAF is needed for complete removal of the pit created in the ending processing time. This is confirmed in Figure 6(b) and 6(h).



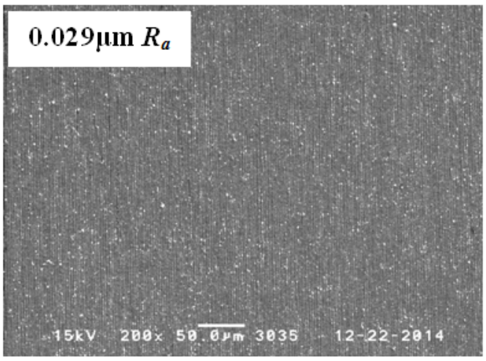
(a) After finishing (2 min EMAF+6 min MAF)



(b) After finishing (2 min EMAF+7 min MAF)



(c) After finishing (2 min EMAF+8 min MAF)



(d) After finishing (2 min EMAF+9 min MAF)

Figure 7. *Surface photograph before and after finishing observed under Scanning Electron Microscope (SEM) with different finishing time combinations for ECM and MAF separately.*

Figure 7 shows the finishing surface photograph of one-stage finishing observed under SEM. In all finishing conditions, the photograph result had showed that initial hairlines have become invisible. This swift process was due to oxidation film formation being constantly removed and created during the initial two minutes of the processing time. Surface improves to 0.029µm R_a for MAF 9 minutes as shown in Figure 7(d).

The advantage of the one-stage process is that simultaneous oxidization of aluminum and removal of oxidation film speed up the planarization process thus shortened the processing time. Since the simultaneous processing of ECM and MAF that have different finishing environment, it is a disadvantage for MAF due to change in viscosity by electrolyte as an additive. In the two-stage processes, it took a total of 8 minutes to achieve 0.028µm R_a, so we predicted it would take 6 minutes for the one-stage process based on time combination. However, the experimental result revealed that it took 11 minutes to achieve similar surface roughness.

The important issue in the combination of the two processes was the finishing environment that affected MAF due to the existence of electrolyte in the slurry, which changes the viscosity. Electrolyte mixed with slurry may also affect the electrochemical characteristic performance of the electrochemical reactions.

5. Conclusions

The results can be summarized as follows.

1) The study revealed that the newly developed finishing method referred as magnetic abrasive finishing with combined electrochemical finishing for finishing of the aluminum tube internal surface using the combination machining jig was successfully performed.

2) The finishing method for one-stage and two-stage finishing method on aluminum tube raw material internal surface had shown finishing time reduction of 60-70%, compared with conventional MAF method that took 30 minutes to achieve similar surface finish.

3) The combination of finishing time of ECM and MAF is critical in producing the improved finishing of the aluminum tube internal surface. The experiment results suggested that finishing time ratio for ECM and MAF is 2:9 to achieve mirror-finished surface or 0.030µm R_a level.

4) The novelty of this paper is in regards to the proposal of the finishing method for aluminum tube internal surface that required a specially designed combination machining tool. The paper studied the surface finishing by the removal of the pits and finishing time reduction was confirmed.

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