Ring-Form Electrode in Electropolishing of External Cylindrical Surface

H. Hocheng and P.S. Pa
(Received Feb. 15, 1999)

Department of Power Mechanical Engineering
National Tsing Hua University
Hsinchu, Taiwan, ROC

Abstract

This paper presents a guide line for the design of ring-form electrode in electropolishing of external cylindrical surface on several die materials. The process can be continuously applied to the traditional turning, form rolling, extrusion or drawing. The electrodes travel along the axis of cylindrical surface of workpiece connected with continuous or pulse direct current. The controlled factors include the chemical composition and concentration of the electrolyte, the electrolyte temperature, the flow rate of electrolyte, and the initial gap width. The experimental parameters are die material, electrical current rating and pulse period, rotational speed of workpiece, rotational speed of electrode, the electrode feed rate, and the electrode geometry. Thin ring and large inner taper angle are associated with large discharge space for the electrolytic products, thus the polishing is more effective. Adequate sharp inner edge radius of the ring electrode provides high current density leading to fast feed rate as well as good polishing. The partial-ring with small cross section and large inner radius is more advantageous. The polishing results with pulse direct current are slightly better than the continuous direct current. However, the use of pulse current raises the machining time and cost. The effects of the electrode design surpass the considerations of the electrical conditions and motion control of workpiece and electrode.

KEYWORDS: Electropolishing, Ring Electrode, Tool Geometry, Partial-Ring, Die Material.

1. INTRODUCTION

Electrochemical machining has been known as a highly effective metal removal method for machining hardened metals at high metal removal rates without residual stress and tool wear. More industrial applications were realized throughout the decades, such as electrochemical drilling, electrochemical grinding, electrochemical deburring, and electropolishing. The process is able to shape the workpiece to a profile approximately complementary to the tool, and the complicated shapes of cathode can be machined from a soft material.

Laboda used water solution NaClO₃ as electrolyte to replace the conventional salt water in order to increase the degree of precision. Due to the concern of burning, NaClO₃ was replaced by NaNO₃ as electrolyte. The production of a desired work anode configuration by the electrochemical machining method requires correct design of the tool cathode. Tool design in ECM is concerned with the prediction of anode (workpiece) shape obtained from a tool under specified conditions of machining. Bannard correlates the current efficiency with current density and flow rate of electrolyte. The maximum efficiency varies with the type of electrolyte. Datta showed that the gap width between electrode and workpiece directly influences the current condition and the discharge dreg of the electrolyte. High-density pulse direct current improves the precision of workpiece, and extends the range of electrochemical surface finishing, while the average current density is lower. The experimental results showed the quality of the machined surface will be influenced by the current density, flow rate of electrolyte and the gap width. Rajurkar et al. obtained the minimum gap width based on Ohm Law, Faraday Law, and the equation of conservation of energy, beyond which the electrolyte will be boiled in electrochemical machining. An on-line monitoring system was proposed.

After rough turning or drawing, the surface roughness of common die materials lies between 3.0 and 6.3 μm. Better surface finish (0.8–1.6 μm) can be produced later through fine turning or grinding. When more severe surface finish (<0.8 μm) is required, subsequent conventional techniques such as polishing by hand or machine are applied. Nevertheless, these techniques heavily depend on the sophisticated experience, and either
hand polishing or machine polishing will result in nonuniform residual stress due to the contact between tool and workpiece. Surface crack and micro voids are often induced and will deteriorate the service life of the parts.

Electropolishing can efficiently produce workpieces of good surface finish and free of the above-mentioned shortcomings. It is well suitable for difficult-to-machine materials. Plastic or press dies, wire-drawing dies, optical and electric parts can apply this technique as well. Its advantages include the production of stress free and burr free surface, absence of chip disposal problem, low overall machining times, and comparatively good surface finish. Shen used NaNO₃ as the electrolyte to proceed the electropolishing on die surface. The result showed that the surface roughness of workpieces decreases with the increase of current density, flow rate and concentration of electrolyte. Moreover, polishing with pulse direct current is found better than continuous direct current. One of the major difficulties of electropolishing is the cost and the design of tool electrode. The authors have developed the electrode geometry in electropolishing of holes. The current study discusses the effect of tool design in electropolishing of external cylindrical surface when turning, form rolling, extrusion, and drawing can hardly achieve the desired fine surface finish for some die materials.

2. REQUIREMENT FOR ELECTRODE DESIGN

The development of the electrode is based on the following considerations:

(1). Applicability to nonrotational workpiece

In case the workpiece (anode) is unable to rotate, such as a rolled or extruded part, the ring-form electrodes (cathode) offer the convenience for electropolishing the whole cylindrical surface in one journey.

(2). Reduction of secondary machining

To ensure the dimensional and geometrical accuracy of the polished surface, the secondary overcutting should be eliminated as much as possible. The ring shape is advantageous for its narrow machining front and therefore is adopted in the current study.

(3). Effective discharge of electrolytic products

The discharge of the electrolytic products out of the gap is crucial for the polishing. The considerations of large inner taper angle, rotation of workpiece and electrode, and design of partial ring and the inside pins will be incorporated into the electrode design.

(4). Fast feed rate

A good electrode design should provide the electropolishing with sufficient electrical current density for fast feed rate in the operation.

(5). Low cost of electrode

One expects the workpiece surface will be electropolished at low cost after turning or drawing, the manufacturability of the electrode should cause no concern.

These considerations leading to the development of the electrode design are illustrated in Fig. 1, the design of the ring-form electrodes is shown in Fig. 2.

3. EXPERIMENTAL

The equipment of electropolishing includes DC power supply, pulse generators, pump, flow meter, electrolytic tank, and filter. The experimental set-up is schematically illustrated in Fig. 3. The materials of experimental workpiece include SKD11, SKD61, NAK80, and SNCM8. Their chemical compositions are shown in Table 1. The cylindrical workpiece is 10mm in diameter and 60mm in length. The amount of the reduction of diameter after electropolishing lies between 0.02mm and 0.2mm, which is included in the design of the process for dimensional control of parts. The initial average surface roughness value (Ra) of the workpiece after rough turning or drawing is from 3.5 to 5.5 μ m.

The electrolyte is NaNO₃ of 25%wt. The flow rate of electrolyte is 41/min. The temperature of the machining is maintained at 25 ± 5°C. Since the temperature has well known effect on the electrochemical process, and the current paper mainly deals with the form design of electrode, it is therefore controlled at constant room temperature. The gap width between electrode and workpiece is 0.3mm. The primary parameters include die material, current rating, the rotational speed of workpiece, the geometry of electrode, the rotational speed of electrode, and the electrode feed rate. The rotational directions of workpiece and electrode are kept the same instead of opposite for stable electrolyte action. Their settings are shown in Table 2.

4. RESULTS AND DISCUSSIONS

Figure 4 suggests there exists an optimal current rating for electropolishing. Excessive or insufficient electrical energy can not effectively reduce the surface roughness. Good polishing is achieved by adequate combination of electrode feed rate and current rating. The principle lies in the optimal energy density across the gap during electropolishing. The workpiece rotation above 400rpm improves the polishing, as shown in Fig. 5. Similar effect of electrode rotation is shown. Both are attributed to that the rotational energy elevates the discharge mobility of dregs. The rotational speed of workpiece above 600rpm associated with fast
electrode rotation produces good polishing. Fig. 6 illustrates the thickness of ring-form electrode plays minor role as compared to workpiece materials. Under the same machining conditions, the polishing effect of SKD61 is the best, followed by SKD11, NAK80, and SNCM8. Thin electrode is preferred for the reduction of the secondary overcutting. To maintain the stability of the gap along electrode feed, a certain thickness is however needed. 3mm is adopted in the current study. Fig. 7 shows that the larger the inner taper angle is, more effective is the polishing. It is more efficient for dreg discharge and concentration of polishing current. The adequate inner edge radius (about 0.5 to 0.75mm radius of curvature) should be taken into consideration, as shown in Fig. 8. If the edge radius is too small (<0.5mm), the current density becomes too large causing violent electrolytic reaction and nonuniformity of the surface finish. On the other hand, large radius results in insufficient polishing energy and rough finish. It is worth noticing that sharp inner edge associated with fast feed rate will keep the current density at the appropriate level, therefore better polishing can be obtained, as shown in Fig. 9. Fig. 10 illustrates that adequate feed rate (1.5 ~ 2.5mm/min) and long pulse-off time is desired for fine finish. The former is related to the optimal current density across the gap, while the latter provides time for removal of the dregs out of the gap. However, the total machining time and cost will increase with the prolonged off-time.

As to the electrode type C, there are short pins inside the ring. The discharge space for the electrolytic products is much more increased, when the polishing is done at the pin top. Fig. 11 and 12 show that a long pin and pin end radius of about 0.5mm produce better finish. Long pins can increase discharge space. Whatever the pin end radius is too large or too small will cause insufficient or excessive current density, respectively. The polishing effect will not be improved when the number of pins increases, as shown in Fig. 13, because the dregs discharge is impeded. One also notices that the electrode with only one pin costs the least. Fig. 14 shows that small diameter of pin is slightly advantageous for increasing the discharge space. Fig. 15 compares the use of rotation of workpiece and electrode. Though the workpiece rotates with electrode is the most beneficial to the polishing, other arrangements are used in different occasions (see Table 3).

Fig. 16 summarizes the contribution to surface finish improvement in use of full-ring electrodes obtained through the workpiece rotation (10%), electrode rotation (11%), electrode feed rate (14%), pulse direct current (12%), electrode thickness (5%), inner taper angle (9%), inner edge radius (11%), pin length (5%), pin end radius (13%), pin number (6%), and pin diameter (4%). The contribution to improvement is compared by the reductions of surface roughness value obtained by the respective design parameters. The electrode feed rate and pin end radius contribute the most to the polishing.

Decreased arc extension of electrode type D is associated with less restricted electrolyte flow and more discharge space, which are advantageous for the polishing, as shown in Fig. 17. Large inner radius (R) of type E provides large discharge space hence slightly improves polishing. It is also advantageous for the polishing in use of decreased height of the electrodes E and F, since the discharge space for dregs is increased. The illustration of these results in graphs is omitted for a concise paper. Fig. 18 shows the contribution to surface finish improvement in use of partial-ring electrodes obtained through the workpiece rotation (9%), electrode feed rate (15%), pulse direct current (12%), electrode thickness (6%), inner taper angle (9%), inner edge radius (11%), arc extension (7%), pin length (5%), pin end radius (12%), pin diameter (4%), electrode height (6%), and inner radius (4%). The electrode feed rate, pulse direct current and pin end radius contribute the most to the polishing.

Fig. 19 shows the polishing results of electrodes from A to F for various materials. One finds that SKD61 is the most suitable material for this process and the electrodes C (with rotation) and F are the best design. SKD61 achieves the fastest feed in electropolishing, when the amount of diameter reduction of other materials remains the same, as shown in Fig. 20. It is believed the current efficiency of SKD61 in electrochemical process is the highest among the four materials. Fig. 21 clearly shows the application of pulse current (100ms/500ms) to type C or F can only improve the surface roughness by 0.07um, while the design change of electrode from A to C or D to F produces much more significant improvement. Thus the use of pulse current is a secondary choice.

The improvement of surface roughness by electropolishing using different electrodes is compared in Fig. 22. The electrodes C and F perform the best among all features. In summary, the average contribution of surface finish improvement obtained through the workpiece rotation (9%), the electrode rotation (10%), using pulse direct current (12%), the electrode feed rate (15%), and the electrode design (54%) is shown in Fig. 23. The design of tool geometry leads to 54% of the improvement, compared to 46% from the influence of the process parameters, such as pulse direct current and motion control of the anode workpiece and the cathode electrode. For the purpose of practical use, the following two sets of conditions are suggested. First, one uses electrode C and 4l/min, continuous DC, 10A, 2mm/3min, ρ
=0.5mm, d=3mm, L=3mm, workpiece and electrode 600rpm, one pin on electrode. Or, one uses electrode F nonrotational and 41/min, continuous DC, 10A, 2mm/min, ρ=0.5mm, d=3mm, L=3mm, H=6mm, workpiece 600rpm, one pin on electrode.

5. CONCLUSIONS

It is effective using the ring-form electrodes in electropolishing for the external cylindrical surface on several die materials after traditional turning, form rolling, extrusion or drawing. The following conclusions can be drawn from the present study. The polishing effect of SKD61 is the most satisfactory, followed by SKD11, NAK80, and SNCM8. High rotational speed of workpiece and optimal feed rate and current produce good surface finish. The ring-form electrode with large inner taper angle and thin thickness are associated with large space for dregs discharge thus improves the polishing. Adequate sharp inner edge radius produces high current density leading to fast feed rate and good polishing as well. The partial-ring with narrow width, small height, and large inner radius providing large discharge space is advantageous. The design change from inner taper to inside pins for both full- and partial-ring electrodes performs well. The electrodes C and F are the best among six features. The pulse direct current is slightly better than the continuous direct current, however, the machining time and equipment cost are increased. The design of electrode contributes more significantly compared to other processing parameters of electrical power supply as well as motion control.

Acknowledgement

The research is supported by National Science Council, Taiwan, ROC, under contract 87-2212-E007-028.

Reference


Table 1 Chemical Composition of Workpiece

<table>
<thead>
<tr>
<th>(Wt%)</th>
<th>SKD11</th>
<th>SKD61</th>
<th>NAK80</th>
<th>SNCM8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>88.65</td>
<td>90.7</td>
<td>92.06</td>
<td>96.48</td>
</tr>
<tr>
<td>C</td>
<td>1.4</td>
<td>0.38</td>
<td>0.13</td>
<td>0.39</td>
</tr>
<tr>
<td>Si</td>
<td>0.4</td>
<td>0.96</td>
<td>0.6</td>
<td>0.3</td>
</tr>
<tr>
<td>Mn</td>
<td>0.3</td>
<td>0.43</td>
<td>1.5</td>
<td>0.9</td>
</tr>
<tr>
<td>P</td>
<td>0.02</td>
<td>0.29</td>
<td>/</td>
<td>0.02</td>
</tr>
<tr>
<td>S</td>
<td>0.03</td>
<td>0.03</td>
<td>/</td>
<td>0.03</td>
</tr>
<tr>
<td>Cr</td>
<td>8.2</td>
<td>5.31</td>
<td>/</td>
<td>0.8</td>
</tr>
<tr>
<td>Mo</td>
<td>0.8</td>
<td>1.08</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Al</td>
<td>/</td>
<td>/</td>
<td>1.12</td>
<td>/</td>
</tr>
<tr>
<td>V</td>
<td>0.2</td>
<td>0.82</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Cu</td>
<td>/</td>
<td>/</td>
<td>1.24</td>
<td>0.03</td>
</tr>
<tr>
<td>Ni</td>
<td>/</td>
<td>/</td>
<td>3.8</td>
<td>2</td>
</tr>
</tbody>
</table>
### Table 2 Experimental parameters and Electrode Types

<table>
<thead>
<tr>
<th></th>
<th>Material</th>
<th>Workpiece</th>
<th>SKD11, SKD61, NAK80, SN3M9</th>
<th>Electrodes: A, B, C, D, E, F</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Power Supply</td>
<td>Current Rating (A)</td>
<td>5, 10, 15, 20, 25, 30 A</td>
<td>Electrodes: A, B, C, D, E, F</td>
<td>F</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pulse On-Off Time (ms/µs)</td>
<td>100/100, 100/200, 100/300, 100/400, 100/500</td>
<td>Electrodes: A, B, C, D, E, F</td>
<td>F</td>
</tr>
<tr>
<td>II</td>
<td>Motion Control</td>
<td>Rotational Speed of Workpiece (rpm)</td>
<td>200, 400, 600, 800, 1000, 1200</td>
<td>Electrodes: A, B, C, D, E, F</td>
<td>F</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rotational Speed of Workpiece (rpm) (with Electrode Rotation)</td>
<td>0</td>
<td>Electrodes: A, B, C</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rotational Speed of Workpiece (rpm) (without Electrode Rotation)</td>
<td>0</td>
<td>Electrodes: A, B, C</td>
<td>F</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Feed Rate of Electrode (mm/min)</td>
<td>0.9, 1, 1.5, 2, 2.5, 3, 3.5, 4</td>
<td>Electrodes: A, B, C, D, E, F</td>
<td>F</td>
</tr>
<tr>
<td>IV</td>
<td>Electrode Design</td>
<td>Thickness of Electrode (t) (mm)</td>
<td>2, 3, 4, 5</td>
<td>Electrodes: A, B, D, E</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Inner Taper Angle (θ) (degree)</td>
<td>0, 10, 20, 30, 40</td>
<td>Electrodes: A, B, C, D, E</td>
<td>F</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Inner Edge Radius (r) (mm)</td>
<td>0.25, 0.5, 0.75, 1, 1.25, 1.5</td>
<td>Electrodes: A, B, C, D, E</td>
<td>F</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pin End Radius (e) (mm)</td>
<td>0.25, 0.5, 0.75, 1, 1.25, 1.5</td>
<td>Electrodes: A, B, C, D, E</td>
<td>F</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pin Length (l) (mm)</td>
<td>2.5, 2.75, 3, 3.25, 3.5, 3.75, 4</td>
<td>Electrodes: A, B, C, D, E</td>
<td>F</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Diameter of Pin (d) (mm)</td>
<td>3.3, 3.5, 4, 4.5, 5</td>
<td>Electrodes: A, B, C, D, E</td>
<td>F</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pin Number</td>
<td>1</td>
<td>Electrodes: A, B, C</td>
<td>F</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Arc Extension of Partial Ring S (mm)</td>
<td>1, 3, 2.3, 3.3, 4, 3.5, 3.75</td>
<td>Electrodes: A, B, C, D, E</td>
<td>F</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Inner Radius (R) (mm)</td>
<td>6.9, 9, 12, 15</td>
<td>Electrodes: A, B, C</td>
<td>F</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Height of Partial Ring (H) (mm)</td>
<td>6.9, 9, 12, 15</td>
<td>Electrodes: A, B, C</td>
<td>F</td>
</tr>
</tbody>
</table>

### Table 3 Application of Ring Electrodes

<table>
<thead>
<tr>
<th>Rotation</th>
<th>Applicable Process</th>
<th>Electrode</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>Rolling, Drawing, Extrusion, Turning</td>
<td>A, B, C</td>
</tr>
<tr>
<td>Yes</td>
<td>Turning</td>
<td>A, B, C, D, E, F</td>
</tr>
</tbody>
</table>

---

**Fig. 1 Development of Electrode Design**

- Easing Secondary Overcutting
- Increasing Effective Current Density
- Requirement
- Design Feature
Fig. 2 Design of Ring Electrode for Cylindrical Workpiece

(a) System Schematics

(b) Configuration of Tool and Workpiece

Fig. 3 Experimental Set-Up

Fig. 4 Electrode polishing at different feed rate of electrode and current rating (SKD61, Type B, 0rpm, 4l/min, continuous DC, t=3mm, θ=40°, r=0.5mm, workpiece 0rpm)

Fig. 5 Electropolishing at different rotational speed of electrode and workpiece (SKD61, Type B, 4l/min, continuous DC, 10A, 2mm/min, t=3mm, θ=40°, r=0.5mm)

Fig. 6 Electropolishing at different electrode thickness (0rpm, 4l/min, continuous DC, 10A, 2mm/min, θ=40°, r=0.5mm, workpiece 0rpm)
Fig. 7 Electropolishing at different taper angle (Type B, 0 rpm, 41/min, continuous DC, 10A, 2mm/min, r=3mm, ρ=0.5mm, workpiece 0rpm)

Fig. 8 Electropolishing at different inner edge radius (Type B, 0 rpm, 41/min, continuous DC, 10A, 2mm/min, r=3mm, θ=40°, workpiece 0rpm)

Fig. 9 Electropolishing at different inner edge radius and feed rate (Type B, 0 rpm, 41/min, continuous DC, 10A, workpiece 0rpm)

Fig. 10 Electropolishing using two techniques at different feed rate (SKD61, Type C, four pins, 600rpm, 41/min, 10A, d=3mm, L=3mm, ρ=0.5mm, workpiece 0rpm)

Fig. 11 Electropolishing at different pin length (Type C, 600rpm, four pins, 41/min, continuous DC, 10A, 2mm/min, d=3mm, ρ=0.5mm, workpiece 0rpm)

Fig. 12 Electropolishing at different pin end radius (Type C, 600rpm, four pins, 41/min, continuous DC, 10A, 2mm/min, d=3mm, L=3mm, workpiece 0rpm)
Fig. 13 Electropolishing at different number of pins (Type C, 600rpm, 4l/min, continuous DC, 10A, 2mm/min, d=3mm, L=3mm, \( \rho =0.5 \)mm, workpiece 0rpm)

Fig. 14 Electropolishing at different pin end radius and pin diameter (Type C, 600rpm, four pins, 4l/min, continuous DC, 10A, 2mm/min, d=3mm, L=3mm, workpiece 0rpm)

Fig. 15 Electropolishing at different arrangement for rotation of workpiece and electrodes (SKD61, 4l/min, continuous DC, 10A, 2mm/min)

Fig. 16 The contribution pie of surface roughness improvement of full ring (SKD61, 600rpm, 4l/min, 10A, 2mm/min, workpiece 600rpm)

Fig. 17 Electropolishing using different arc extension of partial ring (Type D, 0rpm, 4l/min, continuous DC, 10A, 2mm/min, t=3mm, r=0.5mm, \( \theta =60^\circ \), workpiece 600rpm)

Fig. 18 The contribution pie of surface roughness improvement of partial ring (SKD61, 0rpm, 4l/min, 10A, 2mm/min, workpiece 600rpm)
Fig. 19 Electropolishing for various materials
(4l/min, continuous DC, 10A, 2mm/min, workpiece 600rpm)

Fig. 20 Effects of workpiece material on polishing feed rate
(4l/min, continuous DC, 10A, workpiece 600rpm)

Fig. 21 Electrobrightening with different types of electrode using continuous and pulse direct current
(4l/min, continuous DC, 10A, workpiece 600rpm)

Fig. 22 The surface roughness improvement by use of different electrodes
(4l/min, continuous DC, 10A, workpiece 600rpm)

Fig. 23 The contribution pie of surface roughness improvement
(SKD61, 4l/min, 10A, workpiece and electrode 600rpm)