Electropolishing of cylindrical workpiece of tool materials using disc-form electrodes

H. Hocheng*, P.S. Pa

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

Received 2 November 2001; received in revised form 9 March 2002; accepted 14 February 2003

Abstract

This research presents a new application of electropolishing using a low-cost disc-form electrode offering fast improvement of the surface roughness of SKD61. It requires no expensive special-purpose equipment or heavy material removal as conventional electrochemical machining does, and it also avoids the complex pre-polishing of the workpiece before the electropolishing. Round bars or round tubes produced by traditional turning, drawing, form rolling, or extrusion, can be successively electropolished using the designed disc-form electrodes. Five electrode designs are discussed. The experimental parameters include rotational speed of workpiece, electrical current rating and pulse period, electrode geometry, and electrode feed rate. Thinner disc and larger disc taper angle are associated with larger discharge space for the electrode, thus the polishing is more effective. A smaller end radius of the disc electrode produces higher current density and provides faster feed rate and a better polishing effect. A disc with discharge flute performs better, and larger flute back rake angle, side rake angle, wider flute, and deeper flute depth are also advantageous. Although the use of pulsed current slightly outperforms the fluted electrode using continuous current, it sacrifices both machining time and cost. The best electrode design is identified. A guideline for the design of electrodes is provided based on the experimental results.

© 2003 Elsevier Science B.V. All rights reserved.

Keywords: Disc-form electrodes; Electropolishing; Electrode design; Surface roughness

1. Introduction

Various industrial applications of electrochemical machining have been developed for many years since the patent of Gussef, such as electrochemical drilling, electrochemical grinding (ECG), electrochemical deburring, and electropolishing (EP) [1]. The electrochemical honing of cylindrical holes improves dimensional accuracy and relieves surface layer stress [2]. Acharya et al. [3] compared ECM with traditional machining. They concluded the investment cost of ECM is higher, while greater profit and higher quality can be obtained when operated at optimal conditions [3].

Bannard [4] correlates the current efficiency with current density and flow rate of electrolyte. The maximum efficiency varies with the type of electrolyte. Using an electrolyte of NaCl, metal is removed at 100% current efficiency, and the current efficiency is nearly independent of the current density over the anode surface. Using electrolytes NaNO₃ and NaClO₃, current efficiency decreases with decreasing current density, and good dimensional control can be achieved [5]. Laboda used aqueous NaNO₃ as an electrolyte to replace conventional salt water in order to increase the degree of precision. Due to the risk of fire, NaClO₃ was replaced by NaN₂ as electrolyte [6]. Pulsed mode machining is one of the most efficient methods of electrochemical machining of metals, several investigations aimed at improving the parts accuracy and the localization of anodic dissolution [7]. Noto et al. put forward the study of electrode gaps. This suggested the control of workpiece geometry in electrochemical machining [8]. Datta and Landolt showed that the gap width between electrode and workpiece directly influences the current condition and the dregs discharge of the electrolyte [9]. Rajurkar obtained the minimum gap width based on Ohm’s law, Faraday’s law, and the equation of conservation of energy, beyond which the electrolyte will boil in electrochemical machining. An on-line monitoring system was proposed by Rajurkar [10]. Bejar and Gutierrez [11] changed the machining gap width as well as the concentration of electrolyte to investigate the influence upon current efficiency. They found that current efficiency is raised with the increase of current density and electrolytic concentration [11]. Overcut increases with voltage as a result of the
Electropolishing can efficiently finish workpieces of difficult-to-machine materials with fine surfaces. It is suitable for plastic or press dies, wire-drawing dies and optical parts [13]. The experimental results of Mileham et al. showed that the quality of the machined surface will be influenced by current density, flow rate of electrolyte and the gap width [14]. High-density pulsed direct current improves the precision of workpieces. The use of pulsed instead of direct current significantly extends the range of electrochemical surface finishing, and the average current density is lower [6]. Shen used NaNO₃ as the electrolyte for the electropolishing of die surfaces. This result showed that the surface roughness of workpieces decreases with the increase of current density, flow rate and concentration of electrolyte. Moreover, polishing with pulsed direct current is found to be better than continuous direct current [15]. Several methods of electropolishing exist. A soakage bath instead of an electrode is also used in industry. The amount of material removal is extremely low (a few micrometers in depth), thus complicated pre-polishing is often required. Electrochemical grinding can also be used to produce a good surface finish, however, the cost of the equipment is quite high. A comparison of the characteristics of the processes for obtaining a fine surface is shown in Table 1.

The potential for electropolishing is yet to be explored. A process for low cost and rapid improvement of surface finishes requiring no special pre-treatment of workpiece is desirable. The authors have developed electrode geometry in electropolishing of holes [16]. The current study discusses the effect of tool design in electropolishing an external cylindrical surface when turning and drawing cannot achieve the desired fine surface finish for some die materials. After rough turning or drawing, the average surface roughness of common die materials is about 3.0–6.3 μm, a better surface finish (0.8–1.6 μm) can be obtained later through fine turning or grinding [17]. When a surface finish better than 0.8 μm is required, subsequent conventional techniques such as polishing by hand or expensive machining are required. However, they heavily depend on sophisticated experience, and either hand polishing or machine polishing will result in nonuniform residual stress due to the contact between the tool and workpiece. Surface cracks and micro voids are often induced and deteriorate service life. Electropolishing can efficiently produce workpieces free of the above-mentioned shortcomings [13]. An efficient polishing process for external cylindrical surfaces using low-cost electrodes of disc form is desirable. Further to the ring-form and turning tool electrodes [18,19], the current paper discusses the design of innovative disc-form electrodes.

### 2. Electrode design

The development of electrodes is based on the following considerations:

1. **Reduction of secondary machining:** To ensure the dimensional and geometrical accuracy of the polished surfaces, secondary overcutting should be eliminated as much as possible. An electrolyte of NaNO₃ of small throwing power [5] is beneficial in reducing secondary machining. A more concentrated current density is also useful for electropolishing. The use of a disc edge as an electrode is advantageous for this aspect and therefore its performance is further investigated.

2. **Effective discharge of electrolytic products:** The discharge of electrolytic products from the gap is crucial for polishing. Considerations of large disc taper angle, workpiece and electrode rotation, wide and deep discharge flute, and fluted rake angle will be incorporated into the electrode design.

3. **Fast feed rate:** A good electrode design should provide electropolishing with sufficient electrical current density for a fast feed rate during the operation.

4. **Low cost of electrodes:** After turning or drawing, the workpiece surface should be electropolished at low cost. The manufacturability of the electrodes should cause no concern.

Considerations in the development of electrode design are illustrated in Fig. 1, the derived design of the disc-form electrodes is shown in Fig. 2. The forms of electrode are the simple disc (type A with straight-taper edge and type B with round edge), the fluted disc (type C cut from type A and type D cut from type B), and the pin-on-edge disc (type E), which can be considered as an extreme case of a four-flute type D.

### 3. Experimental

This study selects four different die materials which are often used in the mold industry. The materials used for the experimental workpiece are low alloy steels. Their chemical compositions are shown in Table 2. The cylindrical workpiece is 10 mm in diameter and 50 mm in length. The amount of the reduction of diameter after electropolishing varies between 0.02 and 0.2 mm. All workpieces after electropolishing are measured by the surface roughness probe (Hommel T500, the accuracy is within 5%). The surface roughness is characterized by average surface roughness value (Ra), the probe travels perpendicular to the tooth mark. The measured data are obtained as an average from at least two different locations. The initial Ra of the workpiece after rough turning
or drawing is 3.5–5.5 μm. The equipment for electropolishing includes dc power supply, pulse generators, pump, flow meter, electrolytic tank, and filter. The experimental setup is schematically illustrated in Fig. 3. The electrolyte is NaNO$_3$ of 25% concentration. The flow rate of electrolyte is 4 l/min. The machining temperature is maintained at 25 ± 5°C. The gap width between electrode and workpiece is set at 0.3 mm. The electric voltage is controlled at 10 V and the electric current varies in the experiments. The primary parameters include die material, current rating, the rotational speed of electrode, the electrode feed rate, and the geometry of the electrode. Their settings are shown in Table 3.

Table 2

<table>
<thead>
<tr>
<th>Chemical composition of workpieces (wt.%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
</tr>
<tr>
<td>-----</td>
</tr>
<tr>
<td>SKD61</td>
</tr>
<tr>
<td>SKD11</td>
</tr>
<tr>
<td>NAK80</td>
</tr>
<tr>
<td>SNCM8</td>
</tr>
</tbody>
</table>
4. Results and discussion

The experimental results are divided into two parts. The first is the characterization of the basic process parameters, such as current rating, feed rate and rotational speeds, using the basic electrode type A. A set of the parameters able to produce a good surface finish will be identified for the next-stage experiment. The second part discusses the effects of the forms and details of the electrode design using the above mentioned process parameters in the experiment.

4.1. Preliminary experiment of process parameters

Fig. 4 shows that good polishing can be achieved by an adequate combination of electrode feed rate and current rating.
Table 3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotation speed of workpiece (rpm)</td>
<td>200, 400, 600, 800, 1000, 1200</td>
</tr>
<tr>
<td>Rotation speed of electrode (rpm)</td>
<td>0, 200, 400, 600, 800, 1000, 1200</td>
</tr>
<tr>
<td>Current rating (A)</td>
<td>5, 10, 15, 20</td>
</tr>
<tr>
<td>Electrode feed rate (mm/min)</td>
<td>0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4</td>
</tr>
<tr>
<td>Disc thickness (mm)</td>
<td>2, 3, 4, 5</td>
</tr>
<tr>
<td>Disc edge radius (mm)</td>
<td>0.25, 0.5, 0.75, 1.0, 1.25, 1.5</td>
</tr>
<tr>
<td>Taper angle (°)</td>
<td>0, 10, 20, 30, 40</td>
</tr>
<tr>
<td>Back rake angle (°)</td>
<td>0, 10, 20, 30, 40</td>
</tr>
<tr>
<td>Side rake angle (°)</td>
<td>0, 10, 20, 30, 40</td>
</tr>
<tr>
<td>Flute depth (mm)</td>
<td>2.5, 3.3, 3.4</td>
</tr>
<tr>
<td>Flute width ratio</td>
<td>1/1, 1/2, 1/3, 1/4, 1/5</td>
</tr>
<tr>
<td>Pin end radius (mm)</td>
<td>0.25, 0.5, 0.75, 1.0, 1.25, 1.5</td>
</tr>
<tr>
<td>Pin length (mm)</td>
<td>2.5, 2.75, 3, 3.25, 3.5, 3.75, 4</td>
</tr>
</tbody>
</table>

The gap between the disc electrode and workpiece is open when the flute on the disc edge encounters the workpiece. This provides the current-off effect, hence an on-off pulse instead of continuous direct current can be applied. The on-off ratio is set by the rib and flute width on the electrode in the present study, which ranges from 1 to 5.

Fig. 3. Experimental setup.

Fig. 4. Electropolishing at different feed rate of electrode and current rating (type A, 0 rpm, 4 l/min, continuous dc, \( r = 3 \) mm, \( \theta = 40^\circ \), \( R = 0.5 \) mm, workpiece 600 rpm).
Fig. 5. Electropolishing at different rotation rate of electrode and workpiece (type A, 0 rpm, 4 l/min, continuous dc, 10 A, 2 mm/min, $t = 3$ mm, $R = 0.5$ mm, workpiece 600 rpm).

such as 5 A and 1 mm/min, 10 A and 2 mm/min, 15 A and 3 mm/min, and 20 A and 4 mm/min. An optimal amount of electrochemical power input per unit polished length is beneficial to the polishing. Too low or too high electrochemical power causes insufficient polishing or a deteriorated surface, respectively. For a constant feed rate, there exists an optimum current rating for good surface finish and vice versa. Considering both processing time (determined by feed rate) and cost of power supply (determined by current rating), the authors use 2 mm/min and 10 A in the second-stage experiment. The current study also shows the slower the feed rate is, the larger is the reduction in diameter, since the time for material removal at any point becomes longer. Choosing the optimum feed rate at a constant current, one can determine the final diameter after polishing, i.e. 0.03 mm reduction in the current study. This information is essential in process design. Fig. 5 shows high rotational speed of the electrode produces better polishing, since the rotational energy provides better discharge mobility by inducing more turbulent flow of electrolyte. Higher flow rate of electrolyte is advantageous as well, this is set to the maximum (4 l/min) of the current equipment. An adequate workpiece rotational speed (600–1000 rpm) associated with higher electrode rotation produces better polishing. The optimum is determined by the relative size between the electrode and workpiece.

4.2. Experiment of electrode design

The effects of the detailed design for each form group will be examined first, followed by the evaluation of the effects of the form design.

4.2.1. Simple disc form

Fig. 6 shows that the larger the taper angle is, the more effective is the polishing. One considers that either reduced electrode thickness or increased taper angle releases the secondary overcut and provides more open space for dregs discharge. The adequate end radius (about 0.5–0.75 mm) should be taken into consideration, as shown in Fig. 7. If the end radius is too small (<0.5 mm), the current density becomes too large causing violent electrolytic reaction and nonuniform surface finish. On the other hand, the large radius results in insufficient polishing current density and rough finish. It is worth noticing that a small end radius increases the current density, that keeps the input power per unit polished length at the appropriate level, a similar principle is found in Fig. 4. Therefore better polishing can be obtained, as shown in Fig. 8. As the radius is extremely reduced, the effect on the feed rate tends to be cancelled, since the area to be polished is also reduced.

4.2.2. Fluted disc form

Figs. 9 and 10 show that the large flute back rake angle and side rake angle slightly improve the polishing qualify...
for electrodes type C and type D, since the flute inclination can help the electrolytic products be discharged out of the gap through the wide fluted space. One suspects that the deep flute depth also provides mild improvement of the polishing since it provides more open space (see Fig. 11). The authors compared the polishing effect of different flute width of type C and type D. The ratio is defined as the pendent edge to the whole peripheral length. The results show that the flute cut wide is advantageous, since it provides sufficient space and time during electrode rotation for dregs discharge, and reduces the process interference with the electropolishing waste. Fig. 12 further illustrates that the use of the flute. The electrode type C using power supply of constant voltage (10V) and continuous direct current is equivalent to the electrode type A using pulsed direct current. The polishing effect of the latter is only slightly (about 5%) better than the former, but the cost of the power supply is considerably higher and the process cycle time is much increased. A good electrode design, such as the flute can save the production cost, as shown in this example. The use of electrode type C in lieu of type A reduces the average surface roughness from around 0.4 to below 0.3 μm. Fig. 13 shows the contribution to surface finish improvement
Fig. 12. Electropolishing with pulsed direct current of type A and continuous direct current of type C (600 rpm, 4 l/min, 10 A, 2 mm/min, \(t = 3\) mm, \(h = 3\) mm, \(\theta = 40^\circ\), \(R = 0.5\) mm, workpiece 600 rpm).

by use of electrode type C obtained through the disc thickness (11%), the flute width (22%), the flute depth (8%), the flute back rake angle (12%), the flute side rake angle (15%), the taper angle (14%), and the edge radius (18%). The improvement ratio of the surface roughness is calculated by the surface roughness value obtained from individual design parameter of electrode type C divided by the value obtained by electrode type A (2 mm/min, 10 A, \(t = 3\) mm, \(h = 3\) mm, \(\theta = 40^\circ\), \(R = 0.5\) mm). The relative weighting of the contribution of each design feature is then calculated. One finds the flute opening and edge radius contribute most to the polishing.

4.2.3. Pin-on-edge disc form

The design shows short pins attached on the disc (type E). The discharge space for the electrolytic products is much increased (similar to widely opened flute). Figs. 14 and 15 show that long pin and appropriate pin end radius produces better polishing. Long pins can increase discharge space and reduce secondary overcut. Whenever the pin end radius is too large or too small it will produce insufficient or excessive current density, respectively, similar to the effects of the edge radius of electrodes type A and type C. The polishing effect improves when the number of pins is decreased for increasing discharge space, as shown in Fig. 16. There is

Fig. 13. The contribution pie of surface roughness improvement using electrode type C (600 rpm, 4 l/min, continuous dc, 10 A, 2 mm/min, \(t = 3\) mm, \(h = 3\) mm, \(\theta = 40^\circ\), \(R = 0.5\) mm, workpiece 600 rpm).
Fig. 14. Electropolishing using different pin length (type E, 600 rpm, four pins, 4 l/min, continuous dc, 10 A, 2 mm/min, workpiece 600 rpm).

Fig. 15. Electropolishing using different pin end radius (type E, 600 rpm, four pins, 4 l/min, continuous dc, 10 A, 2 mm/min, L = 3 mm, workpiece 600 rpm).

Fig. 16. Electropolishing for different number of pins (type E, 600 rpm, 4 l/min, continuous dc, 10 A, 2 mm/min, L = 3 mm, workpiece 600 rpm).

Fig. 17. The contribution pie of surface roughness improvement, using type E (600 rpm, 4 l/min, continuous dc, 10 A, t = 3 mm, 2 mm/min, workpiece 600 rpm).

Fig. 18. The surface roughness improvement by use of different electrode using continuous and pulse current (600 rpm, 4 l/min, 10 A, 2 mm/min, α, β, θ = 40°, h = 3 mm, L = 3 mm, r = 3 mm, R = 0.5 mm, S = 0.5 mm, workpiece 600 rpm).
an average of 6–7% improvement when the number of pins is decreased by one. The contribution to surface finishing in use of the electrode type E is shown in Fig. 17. The use of type E reduces the average surface roughness further down to near 0.2 μm. The improvement ratio is calculated by comparing the best surface roughness value with the worst value using the individual design parameter of electrode type E. The weighting of performance improvement by single design parameter is thus evaluated.

The improvement of surface roughness using different electrodes is summarized in Fig. 18. The electrode type E performs the best. One also notices the use of pulsed current for the electrodes type A and type B competes with the fluted and pin-on-edge electrodes using continuous current, the polishing time will be prolonged, however.

5. Conclusions

The electropolishing using disc-form electrodes moving along cylindrical workpieces offers the advantages of low-cost equipment, eliminating pre-polishing, low-cost processing, controllable material removal, and effective reduction of surface roughness. This electropolishing can be used for finishing of machined, drawn, rolled or extruded external cylindrical surfaces. The simple-disc electrode with larger taper angle and thinner thickness, which is associated with a larger discharge space, produces a smoother surface. A smaller edge radius produces a higher current density and enables a faster feed rate. For a electrodes with a discharge flute, one finds a larger flute back rake angle and side rake angle, a wider flute, and a deeper flute depth performs better. Electropolishing using simple-disc electrodes and pulse direct current is less effective than the proper use of pulse direct current, but the machining time and cost are increased. There is the equivalent pulsed effect of using continuous direct current, but the machining time and cost are increased. The improvement of surface roughness using different completely inserted electrode, in: Proceedings of the ISEM-8, Moscow, 1986.

Acknowledgements

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

References