The application of a turning tool as the electrode in electropolishing

H. Hocheng*, P.S. Pa

Department of Power Mechanical Engineering, National Tsing Hua University, Hsinchu 300, Taiwan, ROC

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Abstract

In the current study, electropolishing using a turning tool as the electrode for several die materials following turning is investigated. The proposed method uses a traveling electrode instead of the mating electrode as in conventional ECM, hence the dimensional error can be controlled more effectively. Further, the method removes a certain limited amount of material, therefore the complex pre-polishing as required in the soaking electropolishing method is eliminated. This process can be used for various turning operations including end turning, form turning, and flute and thread cutting. Through the attachment of simple equipment, electropolishing can follow the cutting on the same machine and chuck. The electrode of the turning tool travels and polishes the machined surface of workpiece with electrical current. Among the factors affecting the electropolishing, the design of tool electrode is discussed primarily. A common turning tool can be used in electropolishing, while a slight modification of tool geometry achieves optimal polishing at low cost. The controlling factors include the chemical composition and concentration of the electrolyte, the initial gap width, and the flow rate of the electrolyte. The experimental parameters are the current rating, the electrode geometry, the die material, the workpiece rotational speed, and the electrode feed rate. Turning tools with larger angles and smaller cross-section are associated with larger discharge space and thus polish better. The most significant factors in tool design for improving the surface roughness include the end clearance angle and the end cutting edge angle. A smaller nose radius is associated with higher current density and provides a faster feed rate and a better polishing effect. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Electropolishing; Turning-tool electrode; Tool design; Die material

1. Introduction

In the 18th century, Faraday made use of electrical and chemical energy to remove materials and presented the principle of electrochemical machining (ECM) [1]. Gusseff first filed a patent on ECM in 1929. Later, he found that ECM is suitable for alloys of high strength and high melting point. Noto et al. put forward a study of the electrode gap, he suggested it as a means for the control of the workpiece geometry in ECM [2]. More industrial applications were realized throughout the decades, such as electrochemical drilling, electrochemical grinding, electrochemical deburring and electropolishing [3]. Phillips [4] found that the major factors in the removal rate of electrochemical grinding are the conductivity of the workpiece, the rate of decomposition, the current capacity of the power supply, and the composition, concentration, and temperature of the electrolyte. The experimental results of Mileham et al. [5] showed that the quality of the machined surface will be influenced by the current density, the flow rate of electrolyte and the gap width. Bannard [6] correlated the current efficiency with the current density and the flow rate of the electrolyte, the maximum efficiency varying with the type of electrolyte. Datta and Landolt [7] showed that the gap width between the electrode and the workpiece directly influences the current condition and the discharge dregs of the electrolyte.

Electropolishing can efficiently produce workpieces of good surface finish. It is very suitable for difficult-to-machine materials. Plastic or press dies, wire-drawing dies, optical and electric parts can apply this technique also [4]. The electrochemical honing of cylindrical holes improves the dimensional accuracy and relieves the surface layer stress [8]. Bejar and Gutierrez [9] changed the machining gap width as well as the concentration of electrolyte to investigate the influence upon current efficiency, finding that the current efficiency is increased with the increase of the current density and the electrolytic concentration. Shen [10] used NaNO₃ as the electrolyte in electropolishing on a die surface, the results show that the surface roughness of the workpieces decrease with the increase of the current density, the flow rate and the concentration of electrolyte; moreover, polishing with pulse direct current is found to be better than for continuous direct current.
The potential for electropolishing is yet to be fully explored, the main difficulty lying in the cost and the design of the tool electrode. The present authors have developed inserted and feeding electrodes in the electropolishing of holes [11]. The current study discusses mainly the effect of tool design in the electropolishing of an external cylindrical surface when turning cannot achieve the desired fine surface finish for some die materials. The average surface roughness of common die materials from rough turning is about 3.0–6.3 μm, whilst a better surface roughness of 0.8–1.6 μm can be obtained by careful fine turning [12]. However, a surface finish finer than 0.8 μm is often required for many mechanical parts, thus subsequent conventional techniques such as polishing by hand or by machine are applied. These operations depend heavily on sophisticated experience, and either hand or machine polishing can result in non-uniform residual stress due to the contact between the tool and the workpiece. Surface crack and micro-voids are often induced and reduce the service life. Electropolishing can efficiently produce workpieces free of the above-mentioned shortcomings [4]. However, electrochemical grinding requires expensive equipment, while conventional ECM using a mating electrode raises concerns of dimensional error and the shape compensation in electrode design. The method of electropolishing using a soakage bath removes an extremely small amount of material, hence a series of pre-treatment of the workpiece has to be carried out. An efficient low-cost polishing process using a turning tool as the electrode is investigated in the current work.

2. Electrode design

The development of turning-tool electrodes is based on the following considerations:

1. Cost saving of electropolishing. Electropolishing should use existing turning tools as electrodes whenever it is possible, to reduce the cost of the production cycle, since the availability of the electrode will cause no extra concern.

2. Effective discharge of the electrolytic product. The discharge of the electrolytic product from the gap is crucial for the polishing. Considerations of large tool angles and centrifugal force should be incorporated into the electrode design.

3. Reduction of secondary machining. To ensure the dimensional and geometrical accuracy of the polished surface, secondary overcut induced by the working gap should be eliminated as far as possible.

4. Increase of electric current density. A good electrode design should provide the electropolishing with sufficient electrical current density for a faster feed rate in the operation.

The development of the electrode design is illustrated in Fig. 1, and the geometry of the turning-tool electrode is

![Fig. 1. Development of turning-tool electrode design.](image-url)
shown in Fig. 2. The reduction of cross-sectional area and nose radius and the increase of tool angles are related to commonly used turning tools.

3. Experimental work

The electropolishing equipment includes a DC power supply, a pump, a flow meter, an electrolytic tank, and a filter. The experimental set-up is illustrated schematically in Fig. 3. The materials of the workpiece are SKD11, SKD61, NAK80 and SNCM8, of chemical compositions as shown in Table 1. The dimensions of the workpiece are 10.2 mm diameter and 50 mm length. The amount of the reduction of diameter after electropolishing varies between 0.02 and 0.2 mm, depending on the adopted feed rate of the electrode. The initial average surface roughness of the workpiece from turning is 3.5–4.5 μm, the aim being to reduce the value to below 0.8 μm.

The main parameters include the geometry of the electrode, the die material, the rotational speed of the workpiece, and the electrode feed rate. The electrolyte is NaNO₃ of

![Diagram of electrode geometry (Fig. 2)]

Fig. 2. The electrode geometry of the turning tool.

![Diagram of experimental set-up (Fig. 3)]

Fig. 3. Experimental set-up: (a) system schematics; (b) configuration of the tool and workpiece electrode.
25 wt.%. The reason for using NaN₃ lies in that it is quite stable and suitable for a certain amount of material removal, eliminating the need for complicated pre-polishing of the workpiece. The flow rate of the electrolyte is 4 l/min. The temperature of the machining is maintained at 25 ± 5°C. The gap width between the electrode and the workpiece is set 0.3 mm. The current rating is 10 A. The rotational speed of the workpiece is 200, 400, 600, 800, 1000, 1200 and 1400 rpm. The axial feed rate of the electrode ranges from 0.5 to 4.0 mm/min. The various tool angles range from –20° to 40° as shown in Fig. 2. The nose radius is 0.1, 0.2, 0.3, 0.4, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0 and 3.5 mm. The cross-sectional area of the cutting tool is 5 × 5, 7.5 × 7.5, 10 × 10, 12.5 × 12.5, and 15 × 15 mm².

The experiment is divided into three parts. The first part investigates the effects of the parameters in the polishing process, the second part is the primary experimentation of the geometry design of the turning tool, followed by the comparison between the designed tool and a commonly used tool.

4. Results and discussion

4.1. Effects of process parameters

The process parameters include the rotational speed of workpiece, the feed rate of the electrode and the current rating. The mild effect of workpiece rotation is shown in Fig. 4. The range between 200 and 1000 rpm is suggested. Below 200 rpm, the workpiece rotation contributes little to effective flushing, while high-speed rotation often causes the run-out of electrode, which will affect the stability of the gap width; 600 rpm will be used in the following experiments. Fig. 5 suggests an adequate range of tool feed in electro-polishing. High feed rates produce insufficient polishing, while low feed rates worsen the surface finish by excessive material removal. The same good polishing can be achieved by an adequate combination of current rating and electrode feed rate, 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. Fig. 5 suggests that the operation should be carried out at the current rating of 10 A and feed rate of 2 mm/min for the electrode in the present case. Fig. 6 shows that the amount of diameter reduction is inversely proportional to the feed rate for all the tested materials. Small feed rates provide a large amount of

<table>
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<th>wt. %</th>
<th>Fe</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
<th>Al</th>
<th>V</th>
<th>Cu</th>
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<td>SKD61</td>
<td>90.70</td>
<td>0.38</td>
<td>0.96</td>
<td>0.43</td>
<td>0.29</td>
<td>0.03</td>
<td>5.31</td>
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<td>–</td>
<td>0.82</td>
<td>–</td>
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<td>1.40</td>
<td>0.40</td>
<td>0.30</td>
<td>0.02</td>
<td>0.03</td>
<td>8.20</td>
<td>0.80</td>
<td>–</td>
<td>0.20</td>
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<tr>
<td>NAK80</td>
<td>92.06</td>
<td>0.13</td>
<td>0.60</td>
<td>1.50</td>
<td>–</td>
<td>–</td>
<td>0.25</td>
<td>1.12</td>
<td>–</td>
<td>1.24</td>
<td>3.1</td>
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<tr>
<td>SNCM8</td>
<td>96.48</td>
<td>0.39</td>
<td>0.30</td>
<td>0.90</td>
<td>0.02</td>
<td>0.03</td>
<td>0.80</td>
<td>0.25</td>
<td>–</td>
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Table 1

Chemical composition of workpiece

Fig. 4. Electropolishing at different rotational speeds of the workpiece (4 l/min, continuous DC, 10 A, 2 mm/min, R = 1 mm, α, β, γ, δ, ε, ζ = 40°, cross-section = 156.25 mm²).

Fig. 5. Electropolishing at different feed rates and current ratings (SKD61, 4 l/min, continuous DC, R = 1 mm, α, β, γ, δ, ε, ζ = 40°, cross-section = 156.25 mm², workpiece rotation = 600 rpm).

Fig. 6. Correlation between diameter reduction and feed rate (4 l/min, continuous DC, 10 A, R = 1 mm, α, β, γ, δ, ε, ζ = 40°, cross-section = 156.25 mm², workpiece rotation = 600 rpm).
energy input per unit length of tool travel, leading to the deep
removal of material. Hence the diameter control of the
workpiece has to be done by knowledge of this relationship.
The choice of the diameter before polishing depends on the
adopted feed rate of the electrode.

4.2. Effects of geometry design

The geometry design includes various angles, the radius
of the edge nose, and the dimensions of the cross-section.
Fig. 7 shows that the larger is the back rake angle, the more
effective is the polishing, since it produces an inclined plane
which allows the higher flow velocity of the electrolyte
leading to effective flushing along the inclined plane. At
the same time, the electrolytic products and heat can be brought
away more rapidly. The figure also indicates that the effects
of the side rake angle are similar, since the electrolytic
products can be also transported away more effectively from
the side of tool surface, thus the polishing effect is better.
Fig. 8 shows that larger end and side clearance angles
provide a wider space beyond the gap between the work-
piece and the tool nose, which is advantageous for effective
flushing; the effect of the former is more significant than that
of the latter.

Secondary machining can be eliminated effectively with a
larger end cutting edge angle. More space for dreg discharge
is also obtained, thus the polishing effect is better, as shown
in Fig. 9. However, the increase of side cutting edge angle
cause little improvement in polishing. Since the turning tool
does not contact the workpiece, variation of the side cutting
angle in front of the polishing site does not bring noticeable
improvement, as shown in Fig. 9. Decreased cutting edge
width and height are associated with larger electrolyte flow
discharge space, which is advantageous for polishing, as
shown in Fig. 10. Fig. 11 shows that the improvement of
polishing effect is indeed related to the average reduction
ratio of the cross-section of the tool electrode. The reduction
ratio ($K$) is calculated based on the maximum cross-sectional area ($15 \times 15 \text{mm}^2$):

$$K = \left(1 - \frac{A_n}{15 \times 15 \text{mm}^2}\right)$$

(1)

where $A_n$ is the cross-sectional area of 12.5 x 12.5, 10 x 10, 7.5 x 7.5 or 5 x 5 mm$^2$, and the resulting ratios are 31, 56, 75 and 89%, respectively. Fig. 12 shows that the smaller is the nose radius, the more effective is the polishing. However, if the nose radius is too small (<0.4 mm), the current density becomes too large causing violent electrolytic reaction and non-uniformity of the surface finish.

The effects of the tool angle, the nose radius, and the area of the tool cross-section on the surface roughness in electropolishing are summarized in Fig. 13, which shows that the end cutting edge angle is the most potential design factor to be considered, followed by the end clearance angle, the
nose radius, and the back rake angle, while the side cutting edge angle has no effects. The improvement is calculated by the reduction of surface roughness compared with the considered design parameter divided by the best value in that experiment.

Based on the above results, the authors find that the contribution of surface finish improvement obtained through the tool angles is more significant (34%) that of the electrode feed rate (21%), the nose radius (16%), the tool cross-section (16%) and the workpiece rotation (13%). Moreover, the design of the tool electrode, including various angles, nose radii and cross-sectional area, leads to the dominant 66% of the improvement, compared to 34% of the operation parameters, i.e. workpiece rotation and tool feed rate.

4.3. Comparison between designed and commonly used turning tool

The surface roughness of four die materials after electropolishing using a common turning tool was compared with that for the designed tools. The tool angles are generally smaller than those discussed above. The designed tools reduce the surface roughness value to 86% in average for the four tested materials (86% for SKD61, 84% for SKD11, 87% for NAK80 and 88% for SNCM8). This an interesting fact that shows a common turning tool can be used as a tool electrode in electropolishing. Nevertheless, the common turning tool should be slightly modified with increased angles for large discharge space for improved electropolishing; the cost for modification is expected to be low.

5. Conclusions

Electropolishing following traditional turning by a turning-tool electrode is demonstrated. This method uses cost-effective equipment, while both the dimensional error often found in conventional ECM and the need for complex pre-polishing in soakage electropolishing are significantly reduced. Adequate workpiece rotation speed, electrode feed rate and current rating are found in the present case. A turning tool with larger angles and smaller cross-section provides a larger discharge space and produces a smoother surface. The end clearance angle and the end cutting edge angle are the most significant factors in tool design, while the side cutting edge angle plays a negligible role in electropolishing. The nose radius has an optimal value for higher current density, which provides a faster feed rate, and also stable polishing. A commonly used turning tool should be slightly modified following the above-mentioned design principles for improved electropolishing.

References