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Design of Borer-Rib Type Electrode in Electrochemical Smoothing of Large Holes

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This study discusses the electrochemical smoothing and electrobrightening of medium or large holes beyond traditional drilling, boring, turning, or extruding using both inserted and feeding electrodes of borer-rib type for several common die materials. High electrical current is not required when the electrode of borer-rib type is employed to reduce the engaged area for large holes. Traditionally, the hole polishing of a die requires a sequence of complicated premachining or some manual skill. In the current experiment, six types of electrode are completely inserted and connected to both continuous and pulsed direct current, while another six types of electrode are fed into holes using continuous direct current. The design features of the electrodes are of major interest for effective electrochemical smoothing of holes. The controlled factors include the diameter of the electrode as well as the chemical composition and concentration of the electrolyte. The experimental parameters are current density, current rating, electrode design, die material, rotational speed, and feed rate of electrode. For the inserted electrodes, the single-plate electrode performs better than the double-plate electrode, and the single-plate electrode with half borer gives the best polishing effect. Pulsed direct current can slightly improve the polishing effect but at the expense of increased machining time and cost. For the feeding electrodes, the electrode of one-side borer tip with half borer performs the best polishing. It was also found that the electrobrightening after precise boring takes only a short time to make the hole bright, while the electrochemical smoothing saves the need for reaming, making the total processing time less than that required for electrobrightening.

Keywords borer-rib type, electrobrightening, electrochemical smoothing, electrode design

1. Introduction

To achieve fine surface finish of medium or large holes, polishing by hand or machine is employed to follow boring or rough turning for closer dimensional tolerance among the traditional techniques. However, polishing by hand is heavily dependent on the sophisticated skill, and either hand or machine polishing will result in nonuniform residual stress due to the mechanical contact between tool and workpiece. Surface crack and micro voids are often induced and deteriorate the service life of parts. In the case of internal holes produced by electric discharge machining, the brittle surface layer due to carbonation and quench in the process creates additional difficulty for the subsequent process of conventional polishing (Ref 1). More industrial applications such as electrochemical drilling, electrochemical grinding, electrochemical deburring, and electropolishing (EP) were developed (Ref 2). Moreover, EP can overcome the above-mentioned shortcomings and will produce workpieces without residual stress or burr (Ref 3). The production of a desired work anode configuration by the electrochemical machining method (ECM) requires correct design of the tool cathode (Ref 4). It is well suited for difficult-to-machine materials. Plastic or press dies, wire-drawing dies, optical and electric parts are good examples (Ref 5). The experimental results of Mileham et al. showed that the quality of the machined surface will be influenced by the current density, flow rate of electrolyte, and gap width (Ref 6). ECM uses sufficient current density to remove an electrically conductive metal by anodic dissolution when the anode and cathode are separated by a narrow gap containing a high-pressure flowing electrolyte (Ref 7). Bannard correlates the current efficiency with current density and flow rate of electrolyte. The maximum efficiency varies with the type of electrolyte (Ref 8). When using NaCl, metal is removed at 100% current efficiency, and the current efficiency is almost independent of the current density over the anode surface. On the other hand, the aqueous $NaNO_3$ electrolyte can increase the dimensional accuracy. Owing to the risk of fire, the alternative electrolyte $NaClO_3$ was replaced by $NaNO_3$ (Ref 9). Shen used $NaNO_3$ as the electrolyte to conduct EP on die surface. The result showed that the surface roughness of workpieces decreases with increase in current density, flow rate and concentration of electrolyte. Moreover, polishing with pulsed direct current is found to be better than continuous direct current (Ref 10). The gap width between electrode and workpiece directly influences the electrical current condition and dreg discharge (Ref 11). Rajurkar et al. obtained the minimum gap width according to Ohm Law, Faraday Law, and the equation of conservation of energy, beyond which the electrolyte will become boiled in electrochemical machining. An on-line monitoring system was proposed (Ref 12). The use

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of pulsed instead of direct current improves the precision of workpiece and the surface finish, while the average current density is reduced (Ref 13). Schuster et al. showed that the machining resolution is limited to a few micrometers by applying ultra short pulses of nanosecond duration, and microstructures can thus be machined by ECM (Ref 13). The average surface roughness of common die materials after rough turning, extruding, or drawing is about 3.00-6.3 μm. Better surface finish (0.8-1.6 μm) can be obtained through the subsequent fine turning or grinding (Ref 14). Further, conventional techniques such as polishing by hand or expensive machine are applied when surface finish better than 0.8 μm is required. However, these processes depend heavily on human 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 deteriorate the service life of die and mold. EP can efficiently produce workpieces free of the above-mentioned shortcomings (Ref 5). EP is a very effective technique for approaching mirror-like surfaces on many metals. For many applications, a smooth and bright surface is essential and EP is the best technique for this. Additionally, it is recognized that it is easier to maintain the highly polished surfaces in a high state of cleanliness (Ref 15). For EP of internal and external cylindrical surface, various types of electrode were developed (Ref 16-20). Good surface quality of the workpiece was obtained through the arrangement of the experimental conditions. In ECM, when the machining depth increases, structures taper. A disc-type electrode is introduced to reduce the taper (Ref 21).

Electropolishing is a kind of surface-treatment technique, which improves the surface roughness and enhances the surface quality by electrochemical reactions. However, the major difficulty of EP is the cost and the compensation design of tool electrode. There are other existing EP techniques. A comparison of the characteristics between those techniques and the proposed methods is shown in Table 1. The current work aims to develop a fast polishing process with the low-cost electrode eliminating the sequential complicated premachining. EP was conducted with six stationary inserted electrodes and six moving electrodes for die material after boring or turning. Among various factors affecting the electrochemical smoothing and electrobrightening, the design of electrode of borer-rib type is mainly discussed because it not only reduces the need for large power supply but also provides sufficient discharge space.

2. Requirements for Electrode Design

The following are considered in the development of an effective borer-rib electrode.

(1) *Hole size*: For medium or large holes, a borer-rib type electrode can be used practically, which is an important aspect of large-area electrochemical machining. The whole surface of the cylindrical hole wall is also polished by the rotation of electrode.
(2) *Reduction in working time*: For medium or large holes, a completely inserted electrode of borer-rib type can be employed to reduce the working time.
(3) *Reduction in cost of power supply*: A feeding electrode of borer-rib type can be employed at the expense of the increased cycle time for medium or large holes.
(4) *Discharge of electrolytic product*: The discharge of the electrolytic product is more advantageous when the borer-rib type electrode is used, which is an important aspect of large-area electrochemical machining.
(5) *Reduction in secondary machining*: To ensure the dimensional and geometrical accuracy of the polished surface, the secondary overcut induced by the working gap should be eliminated as far as possible.
(6) *Increase in electric current density*: Good finish can be achieved through successful electrochemical smoothing or electrobrightening that requires sufficient electrical current density, and the electrode design should meet this requirement.
(7) *Cost of electrode*: No expensive manufacturing technique should be required for the implementation of the electrode design.

The concept development of the electrode design is described in Fig. 1, and the various created forms are illustrated in Fig. 2.

Table 1 Comparison of polishing methods applying electrochemical principles

	1	2	3	4
Polishing method	Soakage electrochemical polishing	Electrochemical honing	Inserted electrochemical smoothing or electrobrightening	Feeding electrochemical smoothing or electrobrightening
Objective	Brightening/Cleaning	Polishing	Polishing	Polishing
Polishing area	Large	Small	Large	Large
Pretreatment	Mechanical polishing	Reaming Grinding	DrillingBoring Turning	DrillingBoring Turning
Removed depth of materials, μm	Very small (5-10)	Small (10-20)	Controllable (30-200)	Controllable (30-200)
Electrolyte	Acid solutions	Salt solutions/acid solutions	Salt solutions ($NaNO_3$)	Salt solutions ($NaNO_3$)
Polishing time, s	Very long (1200)	Long (300)	Short (30)	Short (30)
Cost of electrode	Low	High	Low	Low
Power supply	Large	Medium/small	Medium/small	Small
Residual stress	Extremely little	Little	Little	Little

3, 4: current research

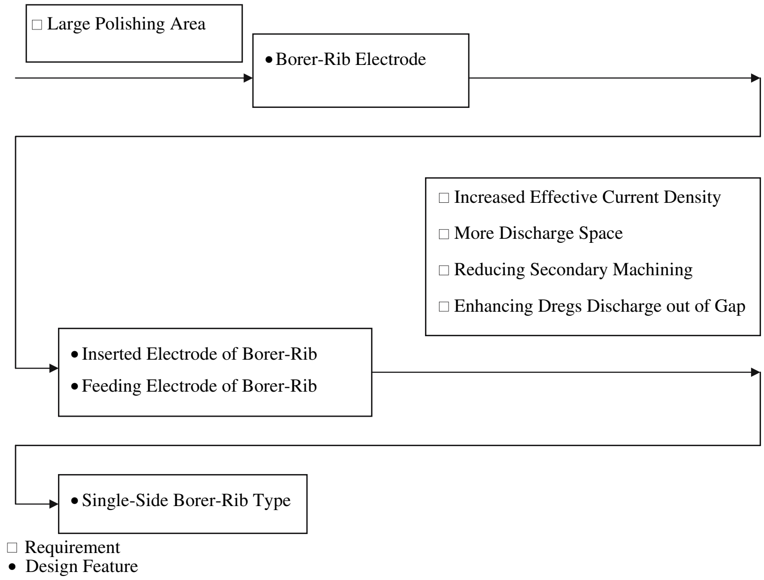

Fig. 1 Development of electrode design

3. Experimental

Figure 3 illustrates the set-up of electrochemical smoothing, which includes a DC power supply, a pulse generator, a pump, a flow meter, an electrolytic tank, and a filter. The materials of the workpiece are AISI H13, AISI D2, AISI P21, and AISI 4340. The chemical compositions are shown in Table 2. The area of the workpiece is 50×30 mm^2. The experiment is divided into two parts; the amount of diameter enlargement by electrochemical smoothing is 0.2 mm and 0.02 mm after electrobrightening, which is designed in the process for dimensional control of parts. The first one proceeds the electrochemical smoothing after the workpiece is prepared by drilling to ψ12 mm and by further boring to ψ39.8 mm. The second one proceeds the electrobrightening after the workpiece is further prepared by precise boring to ψ40 mm for electrobrightening. The hole taper is controlled to be below 0.15°. This is the advantage of using the proposed technique for EP of holes. In this circumstance, the need for the careful premachining process to reduce surface roughness before polishing is eliminated, while the amount of material removed is yet limited and rather uniform; hence, there is no need for geometrical error compensation on the electrode design in case of heavy machining. The preliminary parametric study uses the electrode forms (Type A_i and A_f). The set of process parameters that give the finest surface polishing in this stage is then used in the primary experiment, viz., the design and evaluation of various electrode forms. The main parameters in the first stage include the polishing time and the current waveform (continuous or pulsed direct current). The electrolyte for electrochemical smoothing and electrobrightening uses $NaNO_3$ of 25 wt.%, the solutions include $NaNO_3$ 250 g/l and water 750 g/l. The temperature of the electrolyte is maintained at 25 °C, while ±5 °C does not affect the results. The flow rate of electrolyte is 6 L/min. The side-gap width between the electrode and hole wall varies at 0.2, 0.3, 0.4, 0.5, and 0.6 mm. The rotational speed of electrode is 100, 200, 400, 600, 800, 1000, and 1200 rpm. The completely inserted electrode type A_i is also operated nonrotational. The current density is 15, 30, 45, and 60 A/cm^2, and the current rating is 5, 10, 15, and 20 A. The axial feed rate for the feeding electrodes ranges from 0.5 to 3.5 mm/min. All workpieces after electrochemical smoothing and electrobrightening are measured by the surface roughness measurement (Hommel T500, the accuracy is within ±5% after standard correction). The surface roughness is characterized by Ra, where the length of cut-off is 0.8 mm, and the measuring direction is perpendicular to the tooth mark. The measuring data are at least chosen from two different locations. The aspects of the primary experimental study include the form design of electrode, as will be elaborated in the next section.

4. Results and Discussion

4.1 Preliminary Results of Process Parameters

The side-gap width is set to be 0.3 mm in this study although a tighter side gap between the electrode and hole wall produces a smoother surface. When the gap width is decreased to 0.2 mm, it tends to cause unstable operation, and the electrolyte flushing also becomes more difficult. As to the effect of electrolytic flow rate, the larger the flow rate is, the more rapidly the electrolytic products and heat can be flushed away. At the same amount of material removal, the optimum current density and current rating is found to be 30 A/cm^2 and 10 A, which is a balance between the time needed for polishing and the ease of the discharge of electrolytic product off the gap. For the range of electrode rotation, the centrifugal flow energy is insufficient for effective flushing when the rotation is below 200 rpm. High-speed rotation will affect the stability of gap width, thus worsening the polishing effect. In the current study, the range of electrode rotation between 400 and 800 rpm produces better polishing effect. The radial depth of machining is appropriately 0.1 mm in the current process. Various die materials will show different polishing rates in the electrochemical smoothing process. At the same amount of diameter enlargement of 0.2 mm, the time required for different materials are shown in Fig. 4. As can be seen, AISI H13 needs

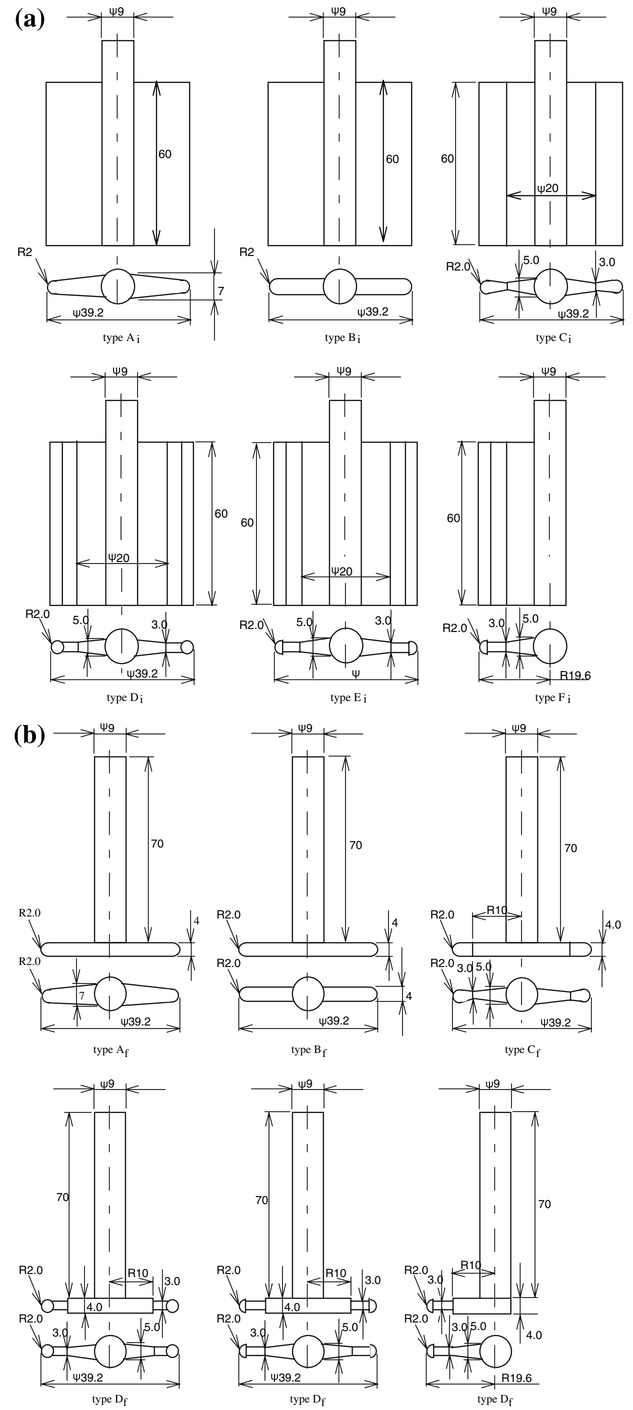

Fig. 2 Design of electrode: (a) Inserted electrodes and (b) Feeding electrodes

the shortest time, and its polishing effect is also the best. Thus, AISI H13 is employed to investigate the effects of various electrode forms on polishing in this study.

4.2 Performance Assessment of Electrode Design

4.2.1 Inserted Electrode of Borer-Rib Type. A boring hole of 39.8 mm in diameter was enlarged to 40.0 mm in diameter by various electrodes. The results of surface finish developed with time are shown in Fig. 5. The hole is polished in 30 s. Type A_i is the simplest plate-form with a wedge edge providing mediocre effect. Type B_i is a straight plate-form, which is slightly better than electrode A_i. Type C_i has a reverse wedge edge, which provides more open space for dreg discharge than the other electrodes. Electrode D_i with a borer on the edge of the plate provides more efficient discharge, which is advantageous for polishing. Type E_i with half borer has more space for dreg discharge, so that the polishing effect of electrode E is better than Type D_i. Type F_i of single plate with half borer obviously has much more space for dreg discharge. At the same time, it also reduces secondary machining and the heat can be removed more rapidly than electrode E_i, so that its polishing effect is the best among the six electrodes. The effect of the pulsed direct current is shown in Fig. 6. Longer off-time is slightly more advantageous, because the discharge of polishing dregs during the off-time is more thorough. However, the total machining time and cost will considerably increase with the prolonged off-time. Comparing Fig. 5 and 6 reveals that electrode F_i also performs the best. The use of pulsed direct current is not as effective as the design change of electrode from E_i to F_i since the application of pulsed current (100 ms/500 ms) to electrode E_i only changes slightly the surface roughness from 0.47 μm to 0.42 μm. Figure 7 shows the distribution of surface roughness improvement obtained by F_i through the borer form (37%), the single plate (39%), and the application of pulsed current (24%). In summary, the use of pulsed current is of limited advantage, particularly when the increased polishing time and cost is considered. While the electrode design of borer form and single plate contributes the maximum enhancement to polishing.

4.2.2 Feeding Electrode of Borer-Rib Type. The results of electrochemical smoothing using feeding electrode A_f at different axial feed rates are shown in Fig. 8. High feed rate does not provide ample time for the polishing effect to be fully developed. On the other hand, low feed rate is associated with more electrochemical reaction per unit time and more dregs in the side gap, thus degrading the polishing effect. The results show that the feed rate of 2.0 mm/min for electrochemical smoothing AISI H13 is optimal. The polishing of AISI H13 is the best, followed by AISI D2, AISI P21, and AISI 4340, similar to the results in Section 4.1 (see Fig. 4). The same good polishing can be achieved by adequate combination of current rating with electrode feed rate (see Fig. 9): 5 A with 1 mm/min, 10 A with 2.0 mm/min, 15 A with 3.0 mm/min, and 20 A with 3.5 mm/min. These combinations imply the principle of an optimal amount of electrochemical energy input per unit polished area. As mentioned above, too low energy does not produce effective polishing, while too high energy often threatens the dreg discharge. Figure 10 compares the electrochemical smoothing at different current ratings through different feeding electrodes. As can be seen, among the six types of electrode, electrode F_f gives the best surface finish at all current ratings. Electrode A_f of borer tips with an axial wedge edge on the leading edge provides mediocre polishing effect. Type B_f with straight form on the borer tips is slightly more advantageous over electrode A_f. Type C_f with a reverse wedge edge on the borer tips provides more open space for dreg discharge than electrode B_f. Type D_f with a bore form provides more sufficient discharge space, which is advantageous for polishing. Type E_f with a half borer form produces more space for dreg discharge and heat can be removed more rapidly than electrode D_f. Type F_f of single-side borer tip with a half borer form obviously has much more open space than the above

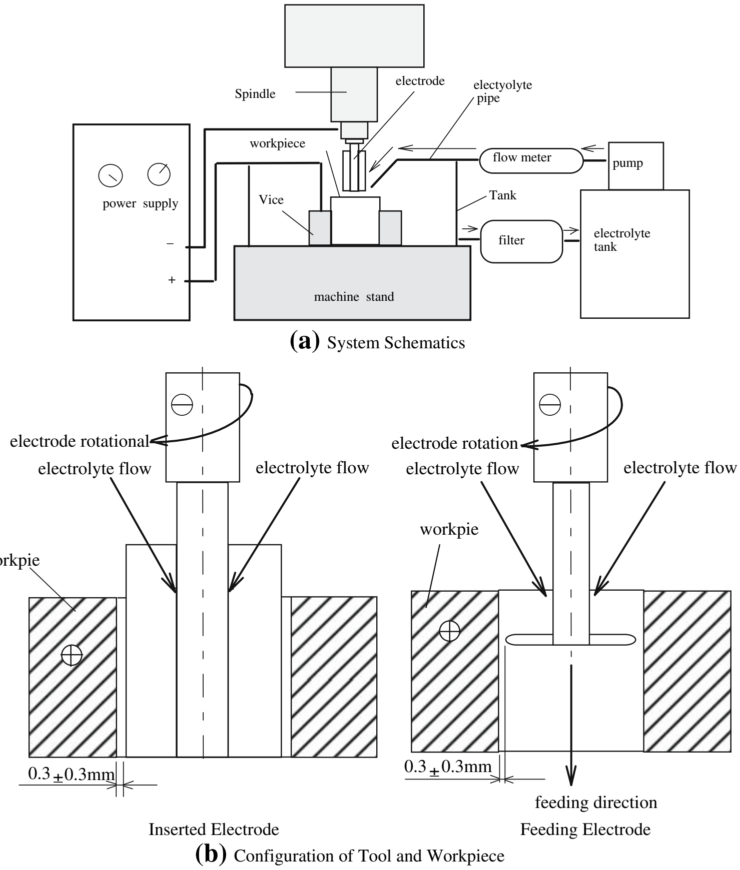

Fig. 3 Experimental set-up: (a) System schematics and (b) Configuration of tool and workpiece

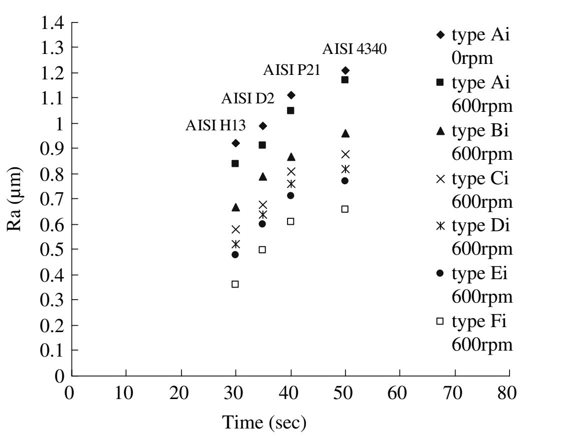

Fig. 4 Electrochemical smoothing with different types of electrode at 0.2 mm of diameter enlargement (61/min, continuous DC, 30 A/cm^2)

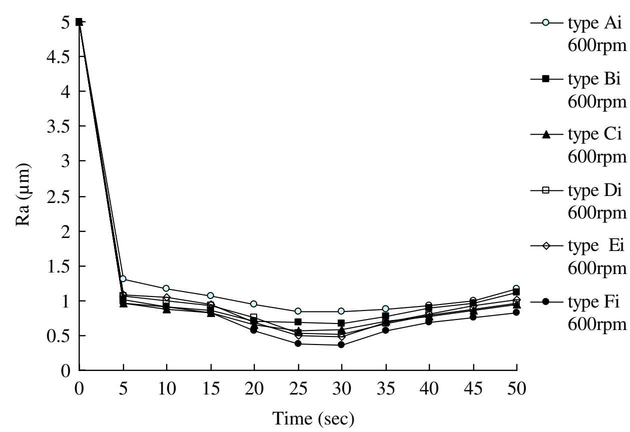

Fig. 5 Electrochemical smoothing with different types of electrode (AISI H13, 61/min, continuous DC, 30 A/cm^2)

Table 2 Chemical composition of workpiece

(Wt.%)	Fe	C	Si	Mn	P	S	Cr	Mo	Al	V	Cu	Ni
AISI H13	90.70	0.38	0.96	0.43	0.29	0.03	5.31	1.08	...	0.82	...	...
AISI D2	88.65	1.40	0.40	0.30	0.02	0.03	8.20	0.80	...	0.20	...	...
AISI P21	92.06	0.13	0.60	1.50	...	...	...	0.25	1.12	...	1.24	3.1
AISI 4340	96.48	0.39	0.30	0.90	0.02	0.03	0.80	0.25	...	...	0.03	2.0

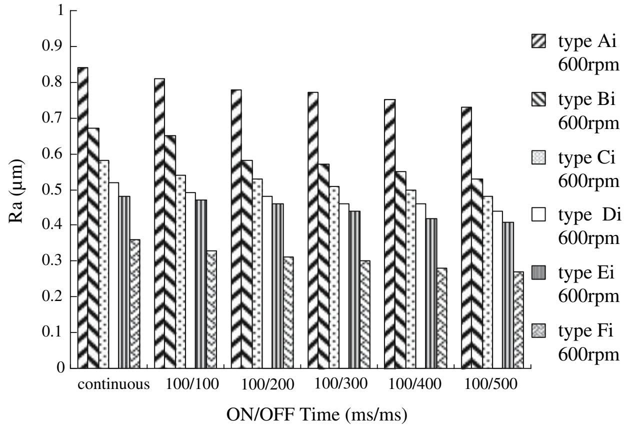

Fig. 6 Electrochemical smoothing with different types of electrode at continuous and pulsed direct current (AISI H13, 61/min, DC, 30 A/cm^2, ON Time 30 s)

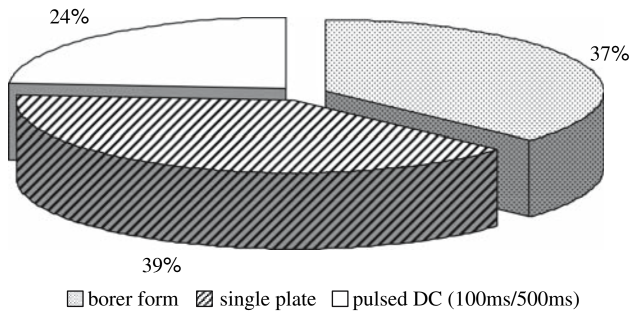

Fig. 7 The contribution pie of surface roughness improvement of electrode F_i(AISI H13, 61/min, 600 rpm, pulse DC, 30 A/cm^2, 100 ms/500 ms)

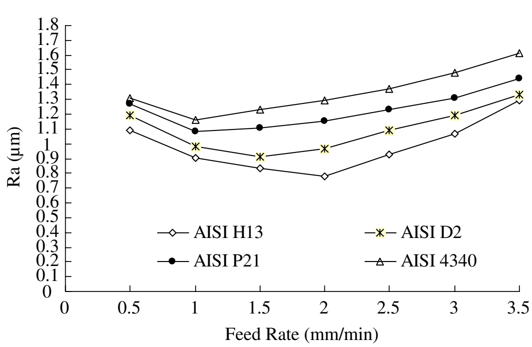

Fig. 8 Electrochemical smoothing with different feed rate of electrode (Type A_f, 600 rpm, 61/min, continuous, DC, 10 A)

five electrodes with double borer tips. It is attributed to its capability of discharging electrolytic dregs, so that the polishing effect of electrode F_f performs the best among the six electrodes. In fact, the reduction in average surface roughness by the use of F_f reaches 60%, compared with merely 8% of A_F. Figure 11 shows the contribution of surface finish improvement obtained by F_f, through borer form (40%), half borer form (29%), and single-side borer tip (31%). A good design of the electrode form in electrochemical smoothing is very effective.

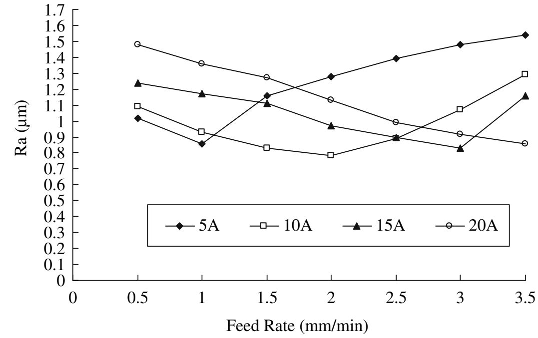

Fig. 9 Electrochemical smoothing at different feed rate of electrode using different current rating (AISI H13, Type A_f, 600 rpm, 61/min, continuous DC)

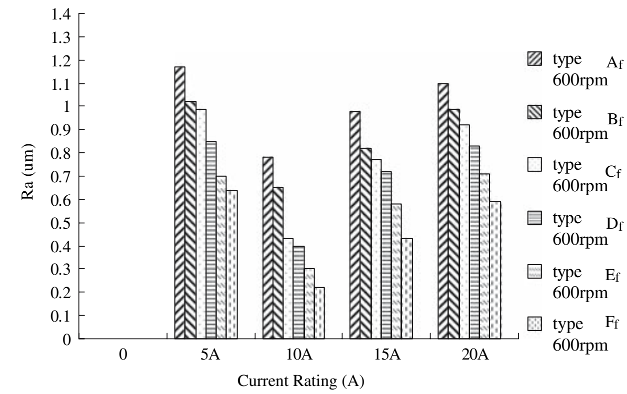

Fig. 10 Electrochemical smoothing at different current rating (AISI H13, 61/min, continuous DC, 2 mm/min)

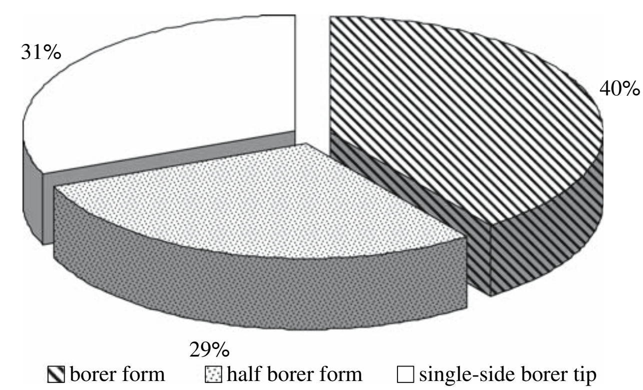

Fig. 11 The contribution pie of surface roughness improvement of electrode F_f(AISI H13, 61/min, 600 rpm, continuous DC, 10 A, 2 mm/min)

4.3 Alternative Electrobrightening Process

Electrobrightening differs from electrochemical smoothing in the amount of material removal, the radial depth of machining is 10 μm compared with 100 μm. A comparison of these two processes is of interest. This method requires the hole prepared through precise boring to ψ40 mm in advance. The average surface roughness after precise boring is around 2.5 μm. Figure 12 shows the surface finish against the working

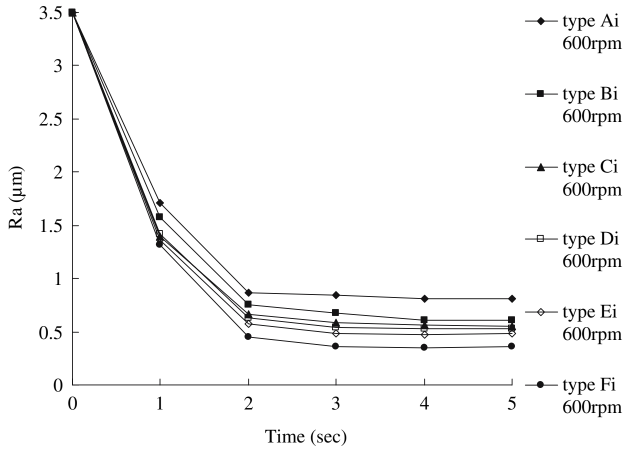

Fig. 12 Electrobrightening with inserted electrodes (AISI H13, 61/min, continuous DC, 30 A/cm^2)

time using various electrodes in electrobrightening. The surface finish obtained and the influence of electrodes are similar to electrochemical smoothing (see Fig. 5), while the time required for finishing is much less (3 vs. 30 s). The electrobrightening greatly reduces the interference of the electrolytic products with the polishing process. As it takes a very short time, the electrolytic rate is low. However, the preceding precise boring increases inevitably the total cycle time. The electrode of single plate with half borer also produces the best effect among the six electrodes. Even the process of electrobrightening is faster, and the polishing effect between these two processes is obviously approximate. However, the alternative electrobrightening increases the total cycle time owing to the requirement of prior preparation by precise boring.

5. Conclusions

The borer-rib type electrodes are suitable for medium or large holes to reduce the cost of power supply in the current investigation. Electrochemical smoothing and electrobrightening can be successfully applied to finishing of boring or turning holes. Rapid polishing using designed electrode is feasible, while the traditional polishing methods require either complicated premachining or some manual skill. Higher flow rate of electrolyte is advantageous, and there exists an optimal rotational speed of electrode and current rating in the process. Various forms of electrode are developed and investigated. One finds that the inserted electrode with discharge flute can slightly improve the surface finish. The electrode of single plate performs better than that of double plate. The electrode of single plate with half borer gives the best polishing effect. The use of pulsed direct current improves slightly the effect of polishing, while it raises the machining cost due to the prolonged cycle time. For the feeding electrodes, the electrode of one-side borer tip with half borer performs the best. Though the polishing time of electrochemical smoothing is longer, the total cycle time is shorter without the need of precision finishing process. The surface roughness obtained from either electrochemical smoothing or electrobrightening is similar.

Acknowledgement

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