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A novel method for micro-gap control in electrogenerated chemical polishing

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ABSTRACT

In the electrogenerated chemical polishing (EGCP), material removal rate (MRR) is inversely proportional to the processing gap. To polish a workpiece with a large area, high and uniform MRR is necessary, which prefers a small and uniform processing gap. Based on the principle of the hydrostatic support, a novel micro-gap control method is proposed. The method uniformly controls the gap between the electrode and workpiece to a micro level over a large area. A relationship between the gap size and the inlet pressure is derived theoretically and verified experimentally. The proposed method is successfully applied to the polishing of a Cu surface with a diameter of 50 mm. Promising results are obtained that surface roughness and flatness are reduced from average roughness (Ra) 82 nm and peak-to-valley (PV) value 290 nm to Ra 4 nm and PV 120 nm, respectively.

1. Introduction

Electrogenerated chemical polishing (EGCP) is a new ultra-precision surface processing technique, and has a great potential for use in ultra-precision machining of defect-free surfaces [1]. The mechanism of EGCP is different from ECM. The polishing mechanism of EGCP is chemical dissolution, and the electrochemical reaction contributes to generating the etchant, while the polishing mechanism of ECM is electrolysis. In EGCP, the redox mediator in polishing solution is changed into an etchant by electrochemical oxidation on an ultra-smooth electrode, and then the workpiece surface is polished through chemical etching by the etchant. The closer the workpiece to the electrode surface, the higher the etching rate, which is called "gap-sensitive etching". Therefore, an ultra-flat working electrode and uniform processing gap are key factors in EGCP. An ultra-flat working electrode is easy to obtain, but a uniform yet small enough processing gap is difficult to achieve. High precision control of the processing gap is necessary when EGCP is used to process large area workpieces. Besides, it is also needed to other gap-sensitive techniques in processing large area workpieces, such as the confined etchant layer technique [2–4] and the electrochemical micro-machining technique using nanosecond pulses [5].

Generally, a micro-gap can be precisely controlled by a positioning system which uses elastic deformation, linear motors, mechanical transmission, solenoids, and so on [6–10]. However, the traditional micro-gap control methods have some inevitable disadvantages that may seriously affect the processing results in EGCP. For example, a piezoelectric actuator (PZT) stack is commonly used for submicron resolution actuation in electrochemical polishing due to its fast response and high sensitivity. However, a micro positioning system based on PZT can only control the relative motion between the tool and workpiece. The distance between the tool and workpiece can be measured by a distance detector or positioning sensor, but such a sensor relies on a complex mechanism for measurement and adjustment. Moreover, the sensor may suffer surface damage between a tool and a workpiece by closed loop force control for zero position detection. Furthermore, the height and inclination of the workpiece surface may fluctuate during the polishing process, which may create difficulties in the stable and real-time control of a micro gap.

Based on the principle of the hydrostatic support, a novel micro-gap control method is proposed. A relationship between gap and inlet pressure is derived theoretically, and dominant factors are revealed. Based on a theoretical analysis, a micro-gap control apparatus is developed and experimental verification of the new gap control method is carried out. The control apparatus is applied to

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EGCP of Cu of 50 mm in diameter and the polishing performance is evaluated.

2. Theory and experiment

2.1. Basic theory of hydrostatic support

The hydrostatic support consists of pushing fluid between the tool and workpiece by means of an external pressurization system [11]. The main advantages of the externally hydrostatic support are no friction and no wear. Moreover, the liquid film in the hydrostatic support produces a parallel micro gap between the tool and the workpiece. This makes it possible that surface pairs based on the hydrostatic support are applied to controlling the gap precisely and in real time.

A schematic diagram of the hydrostatic support is shown in Fig. 1. Pressure within the gap between the workpiece and the tool is against gravity of the tool, and supports the two opposing surfaces separated by a continuous liquid film. The liquid under the center circular region of 50 mm in diameter is static and the pressure is same as outlet pressure. The relationship between input pressure P_{in} and film thickness h underneath the collar is as follows,

$$P_{\mathrm{in}} = P_{\mathrm{p}} + P_{\mathrm{c}} = P_{\mathrm{p}} + P_{\mathrm{p}}\frac{R_{\mathrm{c}}}{R_{\mathrm{h}}} = P_{\mathrm{p}} + P_{\mathrm{p}}\frac{32 l_{\mathrm{c}}}{\pi d_{\mathrm{c}}^4}\frac{h^3 l_{\mathrm{h}}}{3b} \tag{1}$$

where, P_{p} is the liquid pressure in the hydrostatic pocket and it is same as the pressure drop underneath the collar along the radial direction, P_{c} is the pressure drop in the capillary restrictor, R_{c} and R_{h} are flow resistances of the capillary restrictor and the micro gap underneath the collar, respectively, l_{c} and d_{c} are the length and inner diameter of the capillary, b is the width of the collar and l_{h} is the length of midline of the collar (the red dash–dot line shown in Fig. 1). Input pressure P_{in} at the inlet of capillary restrictor is less than the pumping pressure due to the flow resistance of the tube connecting the hydraulic system and the capillary restrictor. The liquid pressure under collar is assumed changing linearly with the flow direction based on the characteristics of fluid flow in parallel gap. The force balance equation of the tool is

$$G = F_{\mathrm{p}} = P_{\mathrm{p}} \times A_{\mathrm{p}} + \frac{P_{\mathrm{p}}}{2} \times A_{\mathrm{h}} \tag{2}$$

where, A_{p} and A_{h} are the projected areas of the pocket and collar on the workpiece surface respectively; F_{p} is the hydrostatic support force; G is the gravity of the tool. Combining Eqs. (1) and (2), one obtains

$$h = \sqrt[3]{\frac{3b\pi d_{\mathrm{c}}^4}{32 l_{\mathrm{c}} l_{\mathrm{h}}}\left(\frac{P_{\mathrm{in}}\left(A_{\mathrm{p}} + A_{\mathrm{h}}/2\right)}{G} - 1\right)} \tag{3}$$

From Eq. (3), film thickness h could be precisely adjusted by changing input pressure, and the order of magnitude of film thickness is dominated by diameter and length of the capillary.

Different from the traditional utilization of a hydrostatic support in the sliding guide or rotary table, film thickness should be tunable through changing the input pressure. From Eq. (3), differentiating film thickness with respect to input pressure, one obtains

$$\frac{\partial h}{\partial P_{\mathrm{in}}} = \frac{h}{3\left(P_{\mathrm{in}} - P_{\mathrm{p}}\right)} = \frac{h}{3\left(P_{\mathrm{in}} - \frac{G}{A_{\mathrm{p}} + A_{\mathrm{h}}/2}\right)} \tag{4}$$

From Eq. (4), film thickness h is sensitive to the input pressure when P_{p} closes to P_{in}. Consequently, it is difficult to precisely adjust. In contrast, when P_{p} is much smaller than P_{in}, the tunable range of input pressure should be large enough to meet the requirement of film thickness alteration. Thus, the flow resistances of the capillary restrictor and the gap underneath the collar should be at the same order of magnitude when designing the floating tool.

The stability of the micro gap is dominated by the stiffness of the hydrostatic support. From Eq. (1), differentiating the liquid pressure in the hydrostatic pocket with respect to film thickness, one obtains stiffness of the hydrostatic support

$$-\frac{\partial F_{\mathrm{p}}}{\partial h} = \left(A_{\mathrm{p}} + A_{\mathrm{h}}/2\right)\frac{3h^2 \Gamma P_{\mathrm{in}}}{\left(1 + \Gamma h^3\right)^2} \tag{5}$$

where,

$$\Gamma = \frac{32 l_{\mathrm{c}} l_{\mathrm{h}}}{3\pi b d_{\mathrm{c}}^4} \tag{6}$$

Maximum value of stiffness is reached when

$$-\frac{\partial^2 F_{\mathrm{p}}}{\partial h^2} = 0 \tag{7}$$

Solving Eq. (7), one obtains

$$h = (2\Gamma)^{-1/3} \tag{8}$$

Substituting Eq. (8) into Eq. (1), one obtains

$$P_{\mathrm{in}} = 1.5 P_{\mathrm{p}} \tag{9}$$

Combining Eq. (9) with Eq. (4), one obtains

$$\frac{\partial h}{\partial P_{\mathrm{in}}} = \frac{h}{1.5 P_{\mathrm{in}}} \tag{10}$$

The film thickness is tunable over a desired range in the process, and the middle value of tuning range is used for designing floating tool. It should be pointed out that the above equations are not closed, and the solution is not single-valued. Eqs. (5), (8), and (10) should be satisfied for a good performance of floating tool. Based on the assigned h, $\partial h/\partial P_{\mathrm{in}}$, and $\partial F_{\mathrm{p}}/\partial h$, the pressure produced by the hydraulic system P_{in} and the gravity of floating tool G can be determined.

2.2. Micro-gap control apparatus

As shown in Fig. 2, the micro-scale large area gap control apparatus mainly consisted of four parts: hydraulic system, floating tool (including capillary restrictors and ultra-flat surface), positioning mechanism, and laser displacement sensor. In order to realize EGCP with this micro-gap control apparatus, three-electrode system (working electrode, counter electrode, and reference electrode) is added.

The hydraulic system ensured the continuous supply of polishing solution and stabilized pumping pressure at the same time. The floating tool could smoothly move in the z direction, corresponding to the distance between the working electrode and copper workpiece. Mass of the tool had an important role in the adjustment of the liquid film formed by the hydrostatic support, while the structure on the floating tool surface affected the film thickness. As shown in Fig. 3, the surface of the floating tool was divided into three hydraulic chambers and a center circular region of 50 mm in diameter. The depth of the non-hatched region was 3 mm. The liquid flow direction is shown as the blue arrows. The liquid flowed into the channel and outer region through the rectangle collar. Each hydraulic chamber had an independent capillary restrictor, and was sealed in the inflow hole. The red dash line shows the midline of one hydraulic chamber. The three hydraulic chambers and their respective capillaries served the function of a self-adjusting mechanism for parallelism of the floating tool. The center circular region had an ultra-flat surface for a sputtered electrode. The hole in the central region provided an electrical connection channel between the working electrode and the external power