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Silicon-based tool electrodes for micro electrochemical machining

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ABSTRACT

Stray current always causes undesired material dissolution in micro electrochemical machining (ECM). The preparation of reliable insulating films on micro electrodes is a critical technique to restrict the stray current, and then improves the machining localization. To meet the requirements for insulating films like good insulation property, thin & uniform thickness and good adhesive strength, a novel method of silicon-based tool electrode is proposed. Heavily doped monocrystalline silicon is used as the electrode body. Silicon dioxide and silicon nitride are deposited on electrode sidewall as insulating films. Through simulations of electrode conductivity, the feasibility of the silicon-based tool electrode is preliminarily verified. Then, a fabrication process of the silicon-based tool electrode is presented. The electrode body is fabricated by wet etching and insulating films are deposited by low pressure chemical vapour deposition (LPCVD). Consequently, the electrodes with section size of $91 \times 52\,\mu m$, 1–2 mm length and 800 nm-thick insulating films are obtained. As the silicon-based electrode is installed on a rotating head in ECM experiments, the electrode with non-circular cross section not only achieves the same effect with a cylindrical electrode, but also is beneficial to removing electrolytic products through the turbulent electrolyte flow. In experimental results, micro grooves with steep sidewall and smooth undersurface (*Ra* 0.42 μm) are machined. Micro holes with inlet diameter of 146 μm and taper angle of 0.58° are obtained. They indicate the feasibility of silicon-based tool electrodes and the effect of insulating films on stray corrosion restriction.

1. Introduction

Micro structures with dimension of tens of microns to 200 μm are typical features necessary to precision components, such as nozzle holes on engine injectors and microchannels on microfluidic chip molds [1,2]. Micro manufacturing methods have to meet the requirements of increasingly higher shape accuracy and surface quality. Micro electrochemical machining (ECM) is an available micro manufacturing method, which is featured with controlled anodic electrochemical dissolution and has the potential to obtain smooth surface [3,4]. In electrochemical reactions, the workpiece is dissolved into ions by an electric current. However, the stray current in lateral gaps always causes undesired material dissolution from micro-structure sidewalls, and then the shape accuracy is deteriorated. How to restrain stray current to improve the machining localization is a primary problem in micro ECM. As a solution, micro tool electrode with reliable insulating film is an effective approach. However, the preparation of micro tool electrodes and reliable insulating films still remains a challenge due to the micro-scale particularities.

Metals are usually used as the electrode body materials due to their good electric conductivity. Up to now, metallic electrodes with diameters of 50–200 μm were obtained by adopting wire electrical discharge grinding [5], electrochemical etching [6] and lithography-electroforming process [7]. Insulating films on electrode sidewall are also widely tried. Chemical vapour deposition (CVD) methods were adopted to deposit silicon carbide (SiC) and silicon nitride(Si_3N_4) as insulating films, a 6.9 μm-thick SiC-Si_3N_4-SiC film was deposited on the molybdenum electrode sidewall [8]. By adopting a drop coating method, a 3 μm-thick enamel film was coated on the tungsten electrode [9]. By using a spin coating method, the 704 silica film with thickness of 5 μm was obtained as the insulating film [10]. In addition, polyimide tubes with wall thickness of 15 μm were used as insulating films [11], which were directly nested on side wall surfaces of micro tools.

The insulating film used in micro ECM particularly requires good insulation property, thin & uniform thickness and good adhesive strength. However, insulating films obtained by above methods cannot completely meet the requirements. For instance, Insulating films with thickness of hundreds of nanometers can be deposited by CVD methods.

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However, the thermal expansion coefficients between metal and silicon compounds have big difference. Since the insulating films are deposited in a high temperature (> 850 °C) but used in room temperature, it results in residual stress and defects between metallic electrode and deposited films, and then the films are easily dropped off in experiments. By using drop coating, spin coating and nesting methods, the insulating films stick to the electrodes by physical coating. It is difficult to achieve compact adhering between electrodes and insulating films. Under the effect of electrolyte soaking, bubble transfer and local heat generation, Insulating films are easily broken. It results in a short lifespan of the insulating film in experiments. Though above metallic electrodes with insulating films were used experimentally, the further development of micro ECM needs micro electrodes with better sidewall insulation properties.

From a novel viewpoint, thin film deposition and microfabrication are pretty mature in silicon process field. Silicon dioxide (SiO_2) and silicon nitride (Si_3N_4) films have excellent insulation properties and can be tightly deposited on monocrystalline silicon substrate. The electrical conductivity of monocrystalline silicon can be improved by heavy doping. Therefore, a type of silicon-based tool electrode for micro ECM is proposed. Instead of commonly used metallic electrode, heavily doped monocrystalline silicon is used as the tool electrode body. SiO_2 and Si_3N_4 are deposited on electrode sidewall as insulating films. At first, the feasibility of heavily doped monocrystalline silicon used as electrode is preliminarily investigated by electrical conductivity analysis. Then the tool electrode body is fabricated by wet etching and insulating films are deposited by LPCVD. By using silicon-based tool electrodes, micro grooves and micro holes are machined in ECM experiments. The feasibility of silicon-based electrodes and the effect of insulating films on stray corrosion restriction are discussed.

2. Design of micro silicon-based tool electrode

Micro-scale dimension, aspect ratio, electrode clamping and electrical conductivity are important aspects in the design of tool electrode for micro ECM. To meet the requirements of high aspect ratio, transversally arranged silicon-based electrodes with non-circular cross section are designed. The electrode is clamped on a rotating mechanism to machine micro structures. A circular envelop curve of front end is formed. Furthermore, the feasibility of the silicon-based tool electrode is preliminarily verified.

2.1. Shape and dimension

Silicon-based tool electrodes with diameter of about 100 μm, high aspect ratio (> 20) and submicron thick insulating films are considered the research targets. The silicon-based electrodes are transversally arranged on the silicon wafer as shown in Fig. 1(a). There are several fabrication cells on the silicon wafer and one of them is shown in Fig. 1(b) and (c). The overall geometrical shape of electrode is fabricated on the front side. Where the l is the length of the electrode, the t is the thickness of the wafer and the h_1 is the etching depth.On the rear side, the silicon wafer is locally thinned. Where the h_2 is the etching depth of rear side and the w is the designed width of electrode. The aspect ratio of the tool electrodes is unlimited in this method. By using anisotropic wet etching on (100) crystal plane, the electrodes with cross section of isosceles trapezoid are fabricated as shown in Fig. 1(a).

As an example, the schematic diagram of the designed silicon-based tool electrode is shown in Fig. 2. The electrode is composed of clamping part and working part. The dimension of clamping part is 8000×6000 μm. Two positioning grooves are fabricated to locate the electrode on the fixture (see Section 4.1), as shown in Fig. 2(a). In order to decrease the contact resistance between silicon-based tool electrode and the power generator in experiments, a patterned metallic film cover the clamping part surface, as shown in Fig. 2(b). The working part is designed with dimension ($w \times h_1$) of 90×50 μm, length of 2 mm. The front end of the tool electrode is heavily doped monocrystalline silicon material and other surfaces are covered by SiO_2 and Si_3N_4 insulating films.

2.2. Clamping of silicon-based tool electrodes

Though the shapes of the silicon-based electrodes are different from that of conventional ones (cylinder electrodes), a circular envelop curve of front end can be formed by rotating the electrode. The schematic diagram of a silicon-based tool electrode used in micro ECM is shown in Fig. 3. The tool electrode is clamped on the fixture, which is driven by the rotating mechanism. The positioning grooves can facilitate the center line parallelism of the electrode and the fixture. In this paper, the diameter of front-end envelop curve is defined as rotating diameter of the silicon-based electrode. In this case, the rotating diameter is determined by the positional relation between geometric centerline of the electrode and centerline of the fixture. When the deviation is adjusted in the range of $0-\delta_0$, the rotating diameter is in the range of about d_1–d_2 ($d_2 = d_1 + 2\delta_0$). By changing in-situ rotating diameters, different sizes of electrodes could be obtained.

In micro ECM, it is a challenge to remove electrolytic products from the inter-electrode gap. Electrolyte outflows from lateral gaps and removes the electrolytic products. Since the lateral gaps in each side are the same by using cylindrical electrodes, the electrolyte flow is in a steady state. Residual electrolytic products remain in the machining zone with the machining depth increasing. By using silicon-based tool electrode with non-circular cross section, the lateral gap along the electrolyte flow direction keeps changing in the range of Δ_1–Δ_2 (Fig. 4). The electrolyte in the machining gap is in a turbulent state and the insoluble electrolytic products are removed smoothly. Comparing to cylindrical electrodes, silicon-based tool electrode could effectively improve the machining stability.

2.3. Electrical conductivity of silicon-based tool electrodes

The electrical conductivity is a primary factor for tool electrodes. Though monocrystalline silicon is semi-conductor of electricity, electrical conductivity of monocrystalline silicon can be significantly improved by heavy doping process. In order to confirm the feasibility of the silicon-based electrode, simulation models consisting of electric current field and current density distribution are established by using COMSOL Multiphysics software. The current density in the inter-electrode gap formed by using electrodes with different electrical conductivity is compared. In the simulations, with the same other simulating conditions, metal (electric conductivity of 1.9×10^7 S/m), heavily doped silicon (electric conductivity of 5×10^4 S/m) and non-doped silicon (electric conductivity of 4×10^{-4} S/m) are used as tool electrodes, respectively.

Fig. 5(a) shows the current density distribution by using the metallic electrode. With an ideal sidewall insulating film, the maximum current density is about 48 A/cm^2 in the inter-electrode gap. Fig. 5(b) shows the simulation results of using heavily doped silicon electrode and the maximum current density is about 35 A/cm^2. Fig. 5(c) corresponding to the non-doped silicon electrode. The specific current density on the workpiece surface are shown in Fig. 6 (see the dashed measuring label in Fig. 5(a)). By using metallic electrode, the current density is about 43.1 A/cm^2 and the current density in lateral gaps is rapidly decreased to 2.4 A/cm^2. By using heavily doped silicon electrode, the current density is about 33.4 A/cm^2, which is 22.5% lower than the former. By using non-doped silicon electrode, the current density is about 2.3 A/cm^2. According to the relationship between current efficiency and current density, the current efficiency of dissolving workpiece material is less than 8% by using the non-doped silicon electrode [12,13]. It can be concluded that the electric conductivity of tool electrode has important effects on the machining efficiency. The machining efficiency of using metallic and heavily doped silicon-based electrode are in the