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Synergistic integrated design of an electrochemical mechanical polishing end-effector for robotic polishing applications

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ABSTRACT

In this paper, we present a novel design of a robotic electrochemical mechanical polishing (ECMP) process. Firstly, the process is presented to replace the conventional ECMP process by a robotic-based one. The advantage of using industrial robots lies in their flexibility, reconfigurability, large workspace and low prices compared to the conventional systems. Secondly, a novel design of a force-controlled end-effector for this purpose is presented. The end-effector is integrated into a macro-mini robot polishing cell. The macro robot (an industrial robotic manipulator) is used to position the mini robot (the proposed end-effector) according to the workpiece profile while the mini robot controls the polishing force. The effectiveness of the proposed device to polish unmilled and milled surfaces has been examined through polishing experiments. The results demonstrate the effectiveness of the presented device to reduce the surface roughness and improve the reflectability and appearance.

1. Introduction

Polishing is a widely used manufacturing process that is used to remove subsurface damages to improve the roughness and to get glossy surfaces [1–3]. Polishing process is playing a critical role in various precision industries such as mould and die manufacturing, aircraft parts (e.g. turbine blades, engine parts, vacuum chambers and landing gear parts), chemical (e.g. polymerize vessels), marine (e.g. ship propellers) and beverage (e.g. hot water tanks).

Presently, most of these processes are primarily conducted manually, which is not only time-consuming and exposes laborers to high noise levels and metal dust environments, but also it is difficult to keep up a steady polishing operation for long time [4]. Labors whom conducting manual polishing for long time are subjected to get "vibration white finger" or other musculoskeletal diseases [5]. Apart from the labor's health, in order to manufacture a mould or die, as an example, the time spent on the polishing process accounts for 37–50 % of the total manufacturing time [6]. Furthermore, some companies may have difficulty in recruiting and training sufficient numbers of highly skilled manual workers to obtain quantitative and qualitative processing [7].

In order to increase the quality and quantity of the production and save the consumed time and cost, some industries are strongly motivated to look for and execute alternative and innovative manufacturing technologies. Automation of the polishing process by computer numerically controlled (CNC) machines or industrial robots is a key solution for this challenge [8–11].

CNC machines have a remarkable positioning accuracy and splendid ability to simultaneously adjust the trajectory, orientation and force during polishing tasks [12]. However, CNC machines have a constrained accessible working space. Thus, only one part should be processed in multiple stages and it definitely confines the extent of the workpiece. Furthermore, to produce surfaces with complex shape, special fixtures and techniques are needed [13].

Industrial robots have some circumstances compared with CNC machines such as low cost, higher adaptability and more prominent of integration with actuators, sensors and different end-effectors. As a result, robotic machining and finishing have attracted many researchers in the recent years [14]. In addition, industrial robots deal with different sorts of workpieces, such as large-sized or complex workpiece without special fixtures. This advantage made the industrial robots an effective and economical solution for material removing process especially from geometrically complex workpieces regardless of the workpiece size [15].

Tailor et al. [16] grouped the polishing processes according to the type of energy source into mechanical, chemical, electrical and electrochemical polishing. These processes do have limitations if they are

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used in an individual manner and not able to meet the demand of industrial manufacture. For instance, an affected zone results on the surface that finished using mechanical as energy source due to generated heat of the friction between the workpiece and the polishing tool. On the other hand, the chemical and electrical polishing processes suffer from low material removal rates. As a result, the surface textures and rough scratches can't be removed by a practical amount.

Integrating the mechanical energy to electrical and chemical energies is defined as electrochemical mechanical polishing (ECMP) technology. Planarization of copper-based chips is an example of ECMP, which is one of the most important processes in the manufacturing of integrated circuits. Electrochemical mechanical (ECM) planarization employs a combined effect of the anodic dissolution and the abrasives' friction from a polishing pad to attend the sample surface [17]. However, planarization is a straightforward process if compared to the case of polishing surfaces with complex shapes and uneven initial surfaces such as plastic or press dies, turbine blades and propellers. Electrochemical grinding (ECG) belongs to the same hybrid group similar to ECMP. Normally, ECMP process follows after ECG. However, the conventional setup of ECG is limited for workpieces with small size because of the restricted workspace of the machine. Furthermore, workpieces with complex shapes should be processed in several stages which is time-consuming.

In order to overcome these limitations, we propose a novel device for robotic ECMP. The invention employs three different polishing actions, electrical, chemical and mechanical in a synergistic way to improve the material removal process. As the proposed device is integrated with an industrial robotic system, ECMP effects can occur in a larger workspace.

The rest of this paper is organized as follows: Section 2 introduces the basic mechanism of the ECP technology and the conventional ECMP with its limitations. Then the proposed design will be given in Section 3. In order to verify the effectiveness of the proposed design, the experimental setup is given in Section 4. The discussion of the obtained results is presented in Section 5. Section 6 gives the conclusions and future works.

2. Conventional ECMP and its limitation

2.1. Basic mechanism in ECP

ECP is a process in which an anodic dissolution of a metallic surface using an electrochemical reaction is used to smooth the surface. The mechanism of the ECP is similar to, but the reverse of, electroplating. In electroplating, an outer thin layer of the object's surface is generated. On the other hand, ECP is used for removing the metal from the object's surface through an electrochemical process.

The mechanism of ECP can be summarized as follows [13,18–21]:

The workpiece to be electro-polished is immersed in an electrolyte and subjected to a direct electrical current under medium voltage. The object is maintained anodic while the cathodic connection being made to a nearby metal conductor. If a DC current is applied, the electrical charge forces metal ions to be dissolved from the workpiece surface (anode). During the process, a varying oxide layer (film) generates and covers the surfaces of the polished object. This film is thickest over micro-depressions valleys and thinnest over micro-projections peaks as shown in Fig. 1. As a result, the electrical resistance is minimum wherever the film is thinnest and vice versa. The difference in current density across the surface is the key to the electro polishing process. In other words, the current density is lesser at the valleys and greater at the peaks. The rate of the electro polishing reaction is directly proportional to the current density. The increased current density at the peaks forces the metal to dissolve faster at these points and thus tends to level the surface material. ECP selectively removes the microscopic peaks much faster than the corresponding rate of attack on the corresponding microscopic valleys. In addition, stock is removed as metallic salt and leaving the surface that is microscopically smooth and free of any blemishes. Gassing in the form of oxygen occurs at the metal surface, furthering the cleaning process.

2.2. ECMP

A disadvantage of the ECP processes is its low material removal rate. Hence, surface textures and rough scratches may not be removed by practical amount. Furthermore, it was reported by some researchers such as Lin et al. [22] that, although the material removal increases slightly as time increases during ECP, a mismatch with Faraday's law occurs after time 400 s. The reason for this phenomenon is attributed to the thin passive film on the anode surface which prevents further reaction. Another interpretation was reported is that there is no forced agitation of the electrolyte because most of the metallic compound may be deposited increasingly back to the anode surface. Moreover, due to rapid dissolution or surface defects and impurity, the reactions at certain place continuous following Faraday's law. This inhomogeneous material removal causes pits on the surface during the transient-passive state [23]. To address this problem, ECMP technology is employed.

ECMP is a compound polishing method that combines electrochemical with mechanical action. The main idea is based on the anodic dissolution as presented in the above subsection. After the passive film is formed on the anode (workpiece) surface under a certain electrochemical parameters, this film is scratched of the surface by abrasives. Hence, a fresh layers of the substrate is immediately exposed to the electrolyte. The mechanical action accelerates the rate of anodic smoothing and increases the removal rate in the high spot region of the anode surface [24]. Approximately 90% of the material is removed through electrochemical action while the mechanical abrasion is controlled to a minimum, just enough to preferentially remove the metal oxide micro-film from the higher spots protruding [25]. Because only a small amount of material is removed by the mechanical action, the polishing tool life is typically ten times longer than that of a conventional mechanical tool [26–29].

ECMP can be categorized according to the conjunction mechanical action to free abrasives (e.g. ECM planarization), bonded abrasives (e.g. ECG) and burnishing force as shown in Fig. 2 [16]. However, ECM planarization machines are designed to deal only with flat surfaces such as copper wafer and stainless steel substrate for thin-film solar cells. On the other hand, ECG machines are fast and very effective on difficult-to-machine alloys such as medical apparatus or parts with complex surfaces such as turbine blades and vanes for aircraft turbine engines. However, the limited available working area of these machines usually leads to process one part in multiple stages. In addition, special fixtures and techniques to produce the surfaces with complex shapes are needed. Moreover, ECMP with burnishing force machines are limited to workpieces with regular shapes. A drawback of these processes is that ECMP of complex workpieces with sculpture surfaces and large size is not possible by such machines. Hence, the ECMP process should be automatized in an innovative way such that the above mentioned limitations can be avoided.

In order to overcome the above mentioned limitations of the conventional ECMP technologies, we present a novel synergistic design of an end-effector with the stat-of-art polishing technologies. In addition, we put forward industrial robotic technology as a basis for the novel automation method of the ECMP technology. As we mentioned before, industrial robots have some advantages such as flexibility, low price and large working envelope. Hence, they are an effective and economical solution for material removing process from geometrically complex workpieces without special fixtures.