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Deterministic removal strategy for machine vision assisted scanning micro electrochemical flow cell

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ABSTRACT

Small cavities on a sliding surface can improve lubrication performance, which has been verified by many researchers. Electrochemical machining (ECM) is an effective way to fabricate this kind of small cavities on a large scale. When the diameter and the removal volume for the cavities are specified, it is still required to efficiently determine the appropriate machining parameters. This paper presents a machine vision based control system for an ECM variant: the scanning micro electrochemical flow cell (SMEFC). The aim of this system is to control the diameter of the cavity in real-time. With the assistance of machine vision, fast acquisition of the machining parameters for the specified diameter and the specified removal volume is possible. The system configuration is first explained in detail, including hardware and software configuration and the image processing algorithms. The latter are based on the Shi-Tomasi corner detector and are used for feedback control, stability and symmetry evaluation of the electrolyte droplet. For convenience, all of these functions have been integrated into a self-developed unified G-code interface. Furthermore, the theoretical explanation for controlling the machining process by vacuum gap (VG) tuning has been investigated through a two-phase flow simulation model, which revealed how the VG influences the shear rate and the pressure difference near the meniscus. Finally, a case study shows how to use the proposed strategy to get suitable machining parameters for a cavity with a diameter of 900 µm and a target removal volume of 0.03 mm^3. This demonstrates the availability of a deterministic removal strategy.

1. Introduction

1.1. Deterministic removal for cavity machining

It is widely known [1–3] that arrays of small cavities on a sliding surface have the potential to reduce friction in sliding pairs, because these cavities provide lubrication and can serve as micro hydrodynamic bearings during sliding. More specifically, the cavity area ratio, cavity depth and cavity diameter have significant influences on the friction performance [4]. In other words, both the cavity area and the cavity volume are important, since the cavity area influences the carrying capacity of the sliding surface and the cavity volume influences the space for the lubricating media. Therefore, it is very important to have a deterministic control of the geometry of the cavities or asperities [5]. In this paper, “deterministic removal” is therefore defined as the case, in which both the specified cavity diameter and the specified cavity volume can be controlled (Fig. 1) simultaneously. When applying a cutting process, it is relatively easy to achieve deterministic removal by optimizing tool design and path planning. Also for laser micromachining advanced modeling and learning techniques have been applied to produce deterministic geometries [6]. On the other hand it is for electro-chemical machining (ECM) difficult to quickly obtain suitable parameters for deterministic machining due to the fact that electrochemical dissolution acts in all directions.

In the ECM domain, jet-ECM and through-mask ECM [7,8], as shown in Fig. 2 (a) and (b), are two frequently applied techniques, enabling the generation of the small cavities without edge lips or burs, and they have been successfully applied in tribology performance improvement [9,10]. As for these techniques, the diameter and the removal volume of the cavities change simultaneously during the electrochemical dissolution. For jet-ECM, it is a common technique to tune the machining current densities and machining time to deterministically achieve specified dimensions of cavities [11–13]. Similarly, the dimensions of cavities fabricated by through-mask ECM methods [14,15] are controlled by the applied voltage (current density), machining time and even the mask wall angle [15]. Simulation models also contribute to the selection of the suitable machining parameters for deterministic removal in jet-ECM and through-mask ECM. Nevertheless,

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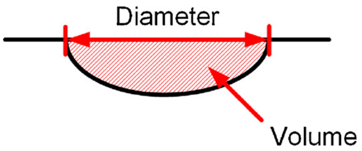

Fig. 1. Schematic of a cavity, where simultaneous control of diameter and volume is required to obtain a deterministic geometry.

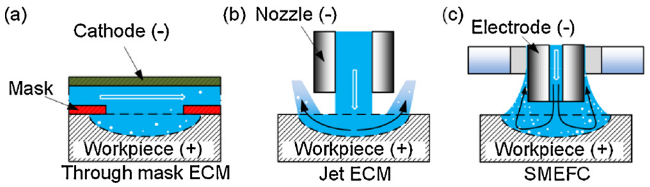

Fig. 2. Schematic of (a) through-mask ECM, (b) jet-ECM and (c) SMEFC.

the searching process for suitable parameters is time-consuming, since a lot of experiments are needed, even in the case of a well-planned design-of-experiments approach.

1.2. Scanning micro electrochemical flow cell

The scanning Micro Electrochemical Flow Cell (SMEFC) (Fig. 2 (c)) principle, as a kind of electrochemical machining method, has been already investigated in the past work of the authors: mesoscale cavities [16] and channels [17] were fabricated by this technique. The principle and schematic of the SMEFC setup are illustrated in Fig. 3. The difference with conventional ECM milling and drilling is the addition of a suction head encircling the hollow electrode. The electrolyte is pumped into the central hole of the electrode as usual. In this case however, the electrolyte will not spread on the workpiece surface, but is sucked back into the suction head through the small gap ring between the suction head and tool electrode. This is realized using fast flowing air around the electrode tip and using the negative pressure generated by a Venturi tube. This method avoids electrolyte splashing and maintains the electrolyte refreshment. As a result, the electrochemical dissolution only happens in the area occupied by the electrolyte and a small cavity will be generated. Because of the specific electrolyte circulation, there is no need for the workpiece to be immersed in the electrolyte, enabling SMEFC to be a portable technique. The cavity ratio can be adjusted by changing the vacuum gap (VG) [16], which is the distance between the bottom surface of the suction head and the workpiece top surface, as indicated in Fig. 3. The fundamental principles governing the cavity ratio will be explained in this work.

Fig. 3(a) also shows the microscope and light source, by which the visual information on the electrolyte droplet in SMEFC can be obtained. This machine vision system makes on-line control of the cavity diameter possible. For jet-ECM and through-mask ECM, due to the invisibility of the flow field in the machining region, this kind of machine vision assisted method is very difficult to realize. When the cavity diameter can be monitored in SMEFC by visual information, it will be easier to control the machining parameters for a deterministic removal, where both the removal volume and diameter of the cavity are specified. This will be further explained in the following paragraphs.

1.3. Machine vision applications in manufacturing

Machine vision, as a powerful monitoring and sensing method, has already substantially improved machine tools' controllability and intelligence. Yan et al. [18] applied a machine vision system in micro-EDM to achieve a new electrode compensation method, which reduced 40% of the machining time compared to the uniform wear method. Fernández-Robles et al. [19] developed a machine vision system to automatically detect broken inserts in edge profile milling heads, which is suitable to be integrated into an on-line machining system. Wang et al. [20] introduced a stereo vision system to automate hybrid manufacturing process planning. Liu et al. [21] utilized a similar system to detect the defect area of metallic components, accelerating the process for automatically targeting the boundary of the defect area. Abdul-Ameer et al. [22] proposed a vision-based sensing utility, consisting of two cameras, to enhance the CNC milling performance. The vision information of which improved the surface roughness by dynamically changing the machining parameters. Sitthi-Amorn et al. [23] applied an integrated machine vision system in a self-developed multi-material 3D printing platform. This machine vision system can achieve self-calibration of printheads, 3D scanning, and a closed-feedback loop to enable print corrections, which simplifies the overall platform design. Supriadi et al. [24] put forward a vision-based fuzzy control method for dieless tube drawing to enhance the dimensional accuracy. Hung et al. [25] proposed using machine vision techniques to assist the re-sharpening process of micro-drills, which make it possible to automatically obtain all required grinding parameters. In addition, many successful applications have been achieved in the welding domain [26–28].

In the sinking ECM process, cameras usually function as an in-situ offline measurement [29–31]. Paczkowski et al. [32] used a Charge-coupled Device (CCD) camera to obtain geometric elements such as inter-electrode gap, working as a basis for the tool electrode position

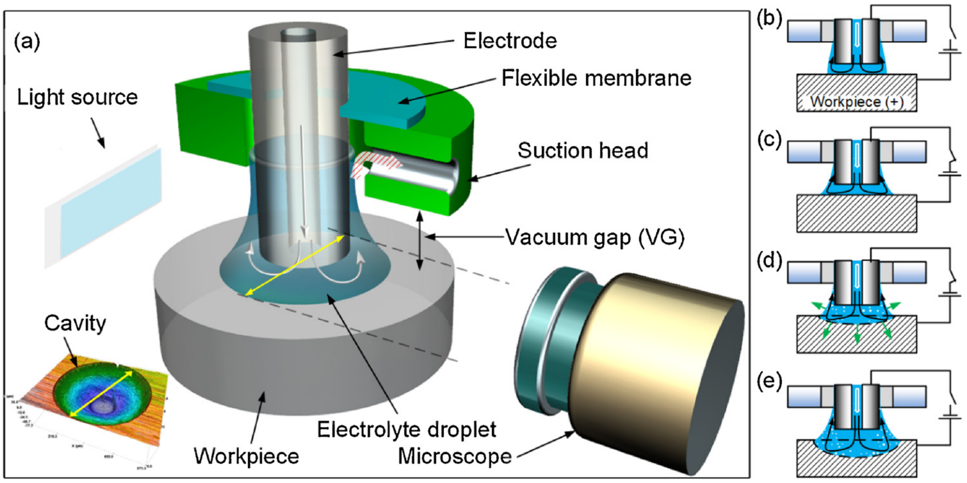

Fig. 3. (a) Schematic of machine vision assisted SMEFC, Working principle: (b) initial moment, without voltage (c) initial moment, with voltage (d) machining in progress (e) final state, without voltage.