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Technical note

A study of micro-EDM and micro-ECM combined milling for 3D metallic micro-structures

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ABSTRACT

Micro-electrical discharge machining (EDM) and micro-electrochemical machining (ECM) combined milling for 3D micro-structure is investigated in this paper. These processes that consist of micro-EDM shaping and micro-ECM finishing are carried out in sequence on the same machine tool with the same electrode but different dielectric medium. The processing conditions are investigated experimentally by the cavity milling. The electrode which was used both in micro-EDM and micro-ECM processes is online fabricated by using an anti-copying block. The EDMed surface roughness of 0.707 μm Ra is lowered to 0.143 μm Ra by applying micro-ECM finishing. Meanwhile, the size and shape of the workpiece by combined milling is controlled precisely, which is much better than that machined merely by micro-ECM. As the large machining parameter values, the machining efficiency is also improved. In order to verify the combined machining performance, some 3D micro-structures were fabricated. The results show that the machining precision and shape accuracy is much better than that machined merely by micro-ECM milling, which can be exactly controlled. Since the EDMed recast layer and surface defects are removed completely, the surface quality and mechanical property of the workpiece is improved, which is better than that machined merely by micro-EDM. It proves that this combined milling method is possible and useful in the field of 3D metallic micro-structure milling.

1. Introduction

Micro-electrical discharge machining (EDM) is widely used in miniature structures machining. It is one of the most effective means of precision and minuteness processing of complicated micro-structures by using a machined electrode shape. Because micro-EDM is a non-contact machining method, it has no cut force between workpiece and electrode. Compared with other micro-machining methods (such as MEMS, LIGA, etc.), it has the characteristics of wide material flexibility, high 3D machining ability, no cut force, etc. The hole in oblique plane can be easily drilled by micro-EDM. It is especially benefited for the machining of complicated structures and special materials. The surface quality of micro-EDM is determined by the width and depth of electrical discharge erosion pits, i.e. the energy of single discharge. And the machining accuracy of micro-EDM is determined by the electrode wear, tool servo stability, and so on. As the fast development of modern power and electron technology, the machining accuracy and surface quality are improved rapidly. However, because micro-EDM is a thermal processing, it may cause deterioration of the machined surface, such as the generation of a recast layer and micro-crack. These surface defects will deteriorate the mechanical property of the workpiece. Moreover, the electrode wear requires the use of many electrodes, which lowers the machining efficiency.

However, micro-electrochemical machining (ECM) as another micro-structure machining method has the important characteristic of no electrode wear. It is not necessary to prepare a number of electrodes, and the machined shape can be easily estimated from the movement path and shape of the electrode. Compared to micro-EDM, micro-ECM has the unique characteristics as below: no heat damaged layer and cracks on the machined surface, the improvement of the surface roughness, micro-ECM can be used in all areas where the electrode and workpiece are located face to face and a current flows [1].

Though micro-ECM has many advantages, it is not suitable for metallic material parts machining. This is because the stray corrosion in micro-ECM process results in the dissatisfactory shape of parts. And the size of the workpiece cannot be controlled precisely. In order to solve this problem, German researchers adopt the nanosecond short pulse power supply to reduce the chemical reaction time on the range of several microseconds. It establishes the foundation of micro-ECM for metallic material [2,3]. The shape

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of the electrode can be copied to the workpiece, this enables the ability of micro-ECM milling for metallic material [4]. Liu et al. did the experimental investigation on complex structures machining by ECM [5]. And a glass workpiece was machined by Cao et al. using micro-ECM [6]. But the size and shape accuracy of these ECMed parts are not very well. In addition, since the low energy, low pulse-on time and frequent short-circuit in micro-ECM process, the machining velocity is very low. It hinders the wide application of micro-ECM for 3D metallic micro-structures. So it is considered that if it is possible to make the machining precision and shape accuracy of micro-ECM milling better, which attains the level of micro-EDM, and make the surface quality better than that machined merely by micro-EDM. Then a combined milling method of micro-EDM and micro-ECM was presented in this paper. It is carried out by micro-EDM shaping and micro-ECM finishing processes in sequence on the same machine tool with the same electrode but different dielectric medium (i.e. EDM oil and ECM electrolyte). The electrode which was used both in micro-EDM and micro-ECM processes is online fabricated by using an anti-copying block.

2. The combined machining system and experimental method

2.1. Micromachining system

The processes of micro-EDM and micro-ECM combined machining are carried out in sequence on the same machine tool with the same tungsten rod electrode but different dielectric medium (i.e. EDM oil and ECM electrolyte) and independent power supply. The machine system having *X*, *Y* and *Z*-axis actuators with 0.1 μm accuracy resolution was set up in this study. The *X* and *Y* axis are driven by AC servo motor, and *Z* axis is driven by a linear motor. The electrode rotation speed can be adjusted from 0 to 4000 rpm. Fig. 1 shows the system configuration of the micro-EDM and ECM combined machine tool.

The electrode which was used both in micro-EDM and micro-ECM processes is online fabricated by using an anti-copying block. The workpiece and EDM oil bath are fixed on the workbench. The ECM electrolysis bath is added after micro-EDM process. So the clamping error of electrode and workpiece can be avoided, and the machining precision is improved.

Micro-ECM is a non-traditional cutting method, and the workpiece material is removed by means of the metal anodic dissolution in the electrolyte. The electrode as a cathode is connected to the power supply, and the workpiece is connected to the anode. The electrode is moved to the workpiece in low speed in the electrolyte, when the gap reaches a certain value, the electric charge exchanges between the workpiece and electrode. Then the workpiece material was dissolved and washed away by the high speed flowing electrolyte. When the workpiece material is stainless steel, the anodic reaction in micro-ECM can be expressed in Eqs. (1) and (2). Since there is no electrode wear, the electrode material does not react with electrolyte. Only hydrogen bubbles are generated around the electrode. The cathodic reaction can be expressed in Eq. (3).

$$Fe - 2e \rightarrow Fe^{2+} \tag{1}$$

$$Fe^{2+} + 2OH^{-} \rightarrow Fe(OH)_2\downarrow \tag{2}$$

$$2H^{+} \rightarrow H_2\uparrow \tag{3}$$

The ferrous hydroxide which is water-fast was formed at the anode and adhered to the workpiece surface and electrode. It hindered the chemical reaction between electrode and workpiece. Most of the existing literatures [7–9] of ECM on steel surfaces deal with the use of acid electrolyte, such as hydrochloric acid and sulfuric acid are always chosen as micro-ECM electrolyte. Korean researchers used the dilute sulphuric acid, and got a better result [10]. But the shape and size accuracy of the workpiece is still not satisfying. And these corrosive electrolytes are harmful to the equipment and human. So the non-corrosive $NaClO_3$ and EDTA solution was chosen in this micro-ECM experiment. $NaClO_3$ solution is a common electrolyte used in electrochemical machining of iron-based alloy. It is a passivation electrolyte, and the machining gap can be reduced as the current density decreases. EDTA is a metal ion complexing agent, which can form a stable water-soluble complex with other alkalis, rare-earth element and transition metal. The electrolyte was supplied with a dropper to the workpiece surface in tempo. And the EDM RC pulsed power is replaced by an ECM rectangular pulsed power with the characteristics of high frequency, narrow pulse-on time and low machining voltage (3–15 V adjustable).

2.2. Experimental method

Due to the high surface roughness, the generation of recast layer and micro-cracks on EDMed surface, it is necessary to use micro-ECM finishing to remove these surface defects after micro-EDM shaping. So the combined machining was investigated in this paper. The processes of micro-EDM shaping and micro-ECM finishing were carried out in sequence on the same machine tool with the same tungsten rod electrode, but independent power supply and different dielectric (i.e. EDM kerosene and ECM electrolyte). Firstly, the 0.5 mm in diameter tungsten rod electrode which used both in micro-EDM and micro-ECM processes was online grinded to 0.1 mm in diameter by a reverse copying block. Then, the workpiece was scanning machined layer by layer in the EDM oil bath by micro-EDM to the depth of 0.185 mm (0.2 mm of total depth). Due to the electrode wear, the electrode should be fed in *Z* direction to compensate the electrode wear. So the EDM machining circle should be repeated several times. Micro-ECM finishing is carried out after EDM shaping. The scanning path is the same as in the case of micro-EDM. The machining time is only once. And there is 15 μm allowance in depth that is to be removed by ECM finishing in the electrolysis bath. The combination of micro-EDM and micro-ECM milling processes was shown in Fig. 2.

3. Basic machining conditions in micro-EDM and micro-ECM milling

To investigate the machining performance of the micro-EDM and ECM combined milling, micro-cavities were carried out under various machining conditions. A tungsten rod with a diameter of 0.1 mm was used as the electrode, and the 304 stainless steel of 0.4 mm in thickness was chosen as the workpiece. The machining voltage, tool feed rate and initial machining gap are varied to investigate the machining performance. In order to enhance the machining efficiency and decrease the micro-EDM machining time, the EDM machining parameters were set bigger than normal value. The rough surface can be removed by micro-ECM. The machining conditions in micro-EDM and micro-ECM were shown in Tables 1 and 2.

4. Results and discussion

The machining performance of the combined milling is mainly controlled by the experimental conditions. As the results of preliminary experiments indicate, the machining parameters such as machining voltage, tool feed rate and initial machining gap have an obvious effect on the ECM machining performance. Since the micro-EDM process is just a roughing process, the following discussion focuses mainly on the essential ECM parameters. The machining