Abstract

論 文 の 内 容 の 要 旨

論文題目　　Research on Micro Electrochemical Machining Using Electrostatic Induction Feeding Method
(静電誘導給電法を用いた微細電解加工の研究)

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This paper describes micro electrochemical machining (ECM) using the electrostatic induction feeding method.

In conventional ECM, the dissolution rate was determined by the current density in electrolyte with the application of DC voltage, thus machining accuracy was limited to spatial resolution of about 0.1 mm. In recent years, the machining accuracy was improved by the application of ultrashort voltage pulse of only nanosecond duration, achieving machining accuracy of nanometer to micrometer range. This technique utilizes the electrode double layer formed on the surface of electrodes. The current density is low in the large gap width, hence, it takes a longer time to form the electric double layer compared to the smaller gap width. By turning off the voltage pulse before the double layer in the large gap is fully developed, the electrochemical reaction can be localized at a small gap width by using ultrashort pulse duration current, because the electrochemical dissolution only occurs at the place where the electrical double layers are fully charged during the short pulse duration. On the other hand, with the newly developed electrostatic induction feeding method, pulse current of several tens of ns in pulse duration can be easily obtained without the use of an expensive ultrashort pulse generator. In addition, this method enables non-contact electric feeding by replacing the feeding capacitance C_1 with a gap between the feeding electrode and rotating spindle, allowing high speed rotation of the tool electrode.

First, the principle of electrostatic induction feeding ECM was discussed in Chapter 2.

Then in order to avoid short circuit in the small working gap of several micrometers, a servo feeding control system based on monitoring the peak of gap voltage was developed. Compared with the old method, which monitors the average of peak gap voltage, controllability of the working gap width with a higher response was obtained because of the higher S/N ratio.

In Chapter 4, micro-rods were machined by electrochemical machining using the electrostatic induction feeding method. Based on the previous research results in Chapter 3, the peak voltage method was used to control the feeding of workpiece during micro-rods machining, and the experimental results were described. A tungsten plate and stainless steel (SUS304) rod were used as tool electrode and workpiece, respectively. The workpiece can be fed either in axial or radial direction to fabricate a micro-rod. When the workpiece was fed in the axial direction normal to the top surface of the tool electrode, the diameter of micro-rod was determined by the depth of cut in the radial direction, and length of micro-rod was determined by the feed distance in axial direction. The influences of voltage amplitude, thickness and surface area of tool electrode on the machining characteristics were investigated from the aspects of machinable length limitation, straightness of micro-rod and surface finish to improve the machining accuracy. The results of machining experiment and current density simulation showed that the influence of stray current on the machining accuracy was obviously decreased by decreasing the thickness of tool electrode, thereby micro-rods with higher aspect ratio and better surface finish were fabricated. However, the influence of the top surface area of tool electrode on machining accuracy was small due to the significantly small change in the average current density on the shoulder surface of workpiece, resulting in small change in material removal rate (MRR), with different top surface areas of tool electrodes. In addition, when the workpiece was fed in radial direction, the limit of the maximum length of the micro-rod was shorter due to the stray current flowing through the end of the micro-rod during all the machining time. The simulation results of the material removal process were qualitatively in agreement with the experimental results.

In Chapter 5, to improve the machining accuracy of micro-rod, the influence of the annealing process of the workpiece and different electrolytes on the machining characteristics were investigated. The machinable length limitation was decreased with the annealed workpiece due to the influence of corrosion. It is considered that the annealing process damaged the workpiece, because the annealing process was not completed in a protective gas atmosphere. Then the machining characteristics with the different electrolytes of NaCl and $NaNO_3$ aqueous solution were investigated with feeding the workpiece in axial direction method. It was found that the influence of pitting corrosion was eliminated with the electrolyte of $NaNO_3$ aqueous solution. This is because the chloride ion is a tiny and aggressive ion compared with the nitrate ion, and easily penetrates the passive oxide layer on the surface of metal resulting in the higher occurrence probability of pitting corrosion. With the $NaNO_3$ aqueous solution, micro-rod with the high aspect ratio of 20 was easily machined. Compared with EDM, the electrochemical reaction was difficult to be localized in a small working gap with the ECM method resulting in the low machining accuracy. Therefore, the EDM has an obvious advantage in the miniaturization of size compared with the electrostatic induction feeding ECM. However, there is no residual stress and cracks generated in ECM and the surface roughness is better. Hence, there is a possibility that the machining accuracy and miniaturization limit of ECM will be able to exceed the machining ability of EDM in the future.

In Chapter 6, the influences of different materials, including the tungsten, high-speed steel (SKH51) and tungsten carbide, on the machining characteristics were investigated with the electrostatic induction feeding ECM. When the tungsten is used as workpiece material, bipolar current is needed for machining, because of the influence of the tungsten oxide layer generated on the surface of workpiece which is not conductive.

Compared with the ECM, the EDM has an obvious advantage in the machining tungsten and tungsten carbide. Since the process is based on thermal erosion of metallic materials, EDM can be used for any difficult-to-machine materials regardless of electrochemical properties. However, because EDM is a thermal process, the machined surface is characterized by recast layers, including cracks and residual tensile stresses, which result in overall degeneration of the component’s mechanical capabilities. In contrast, ECM relies on the mechanism of anodic electrochemical dissolution to remove material, with the advantage that the machined surface has no recast layers and is free of residual stress and micro cracks. The main problem in ECM is to create conditions for the electrochemical dissolution localization, because during machining the area of dissolution is larger than the area of the electrode tool (machining delocalization).

In Chapter 7, a hybrid machining of micro-ECM and micro-EDM in the same setup and same electrolyte was proposed by utilizing the passive oxide layer formed on the surface of tungsten electrode. The conversion of EDM and ECM modes can be realized using the passive oxide layer formed on the surface of the tungsten electrode. To switch to the EDM mode, a diode is placed in parallel with the working gap so that the pulse voltage can be applied to the gap when the polarity of the tungsten tool electrode is positive. Thereby, the oxide layer is left on the tool surface, generating arc discharges in the gap. To switch to the ECM mode, the diode is removed to obtain the bipolar pulse current in the gap. Thus, the oxide layer cannot be formed on the tool surface, realizing the electrolytic dissolution of the workpiece.

As a conclusion, the machining accuracy and limit of miniaturization of the electrostatic induction feeding ECM are becoming equivalent to micro EDM. Considering the advantages of ECM: no residual stress, no cracks, and better surface roughness, micromachining processes which are now performed by micro EDM can be replaced by the present ECM method. However, there are some disadvantages, such as the low material removal rate (especially in micro ECM) compared with the EDM method, and difficulty to machine metallic materials, such as W, WC, Pt, and Au, which can be easily machined using the EDM method. Hence, the hybrid machining of micro-ECM and micro-EDM in the same setup and same electrolyte was proposed. The machining process was converted to EDM mode with the oxide layer formed on the surface of tungsten electrode, and ECM mode without the oxide layer. The generation of the oxide layer was controlled by a diode placed in parallel with the working gap with the bipolar current. With the hybrid system, difficult-to-machine materials can be machined using the EDM mode. Rough machining can also be performed using the EDM mode, while the ECM mode is used for the requirement of a high surface finish.

In the future, machining of various kinds of materials, drilling holes with high aspect ratio and ECM milling of 3D shapes with simple shaped electrode should be investigated furthermore with the electrostatic induction feeding ECM.