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Convex shaping process simulation during counter-rotating electrochemical machining by using the finite element method

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Abstract In counter-rotating electrochemical machining (CRECM), a revolving cathode tool with hollow windows of various shapes is used to fabricate convex structures on a revolving part. During this process, the anode workpiece and the cathode tool rotate relative to each other at the same rotation speed. In contrast to the conventional schemes of ECM machining with linear motion of a block tool electrode, this scheme of ECM is unique, and has not been adequately studied yet. In this paper, the finite element method (FEM) is used to simulate the anode shaping process during CRECM, and the simulation process which involves a meshing model, a moving boundary, and a simulation algorithm is described. The simulated anode profiles of the convex structure at different processing times show that the CRECM process can be used to fabricate convex structures of various shapes with different heights. Besides, the variation of the inter-electrode gap indicates that this process can also reach a relative equilibrium state like that in conventional ECM. A rectangular convex and a circular convex are successfully fabricated on revolving parts. The experimental results indicate relatively good agreement with the simulation results. The proposed simulation process is valid for convex shaping prediction and feasibility studies as well.

1. Introduction

With the rapid developments in the aerospace industry, there is an increasing requirement for processing technology of high-strength, low-weight, metallic, and intermetallic materials such as titanium alloys and nickel-based super alloys.[1,2] Unlike traditional machining methods, the electrochemical machining (ECM) process is an anodic electrochemical dissolution process, which can effectively remove difficult-to-cut materials without tool wear, machining stress, and plastic deformation.[3,4]

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In recent years, many industrial applications have been successfully yielded by using ECM. A high-efficiency ECM method of blade integrated disk (blisk) channels was proposed.[5] By controlling the space trajectories of three stainless steel tubes, three blisk channels could be produced at the same time with good quality. ECM also achieved good performance in inner surface polishing of gun barrel chambers.[6] Micro-dimple arrays on cylindrical inner surfaces have been fabricated during electrochemical micromachining using a dry-film photoresist.[7] In addition, ECM has been used to machine titanium work samples for biomedical applications.[8]

There are many revolving parts in the aerospace industry such as rocket engine parts and jet engine rings.[3] These revolving parts are usually thin-walled and have many convex structures with various shapes on the surface. In conventional sinking ECM, multiple working stations are needed to obtain a required surface profile. According to the different shapes of the convex structures, more than one tool electrodes have to be prepared. For example, as reported in the ECM of aero-engine casing, eight block tool electrodes were used to complete the machining in as many as fifteen working stations.[9] Besides, a secondary processing is sometimes needed to remove the rib-like remnants on the anode surface which are caused by tool replacements and inlets of the electrolyte. This results in a time-consuming and high-cost machining process. Counter-rotating electrochemical machining (CRECM) was proposed to fabricate convex structures on a revolving part.[10] During this process, a revolving cathode tool with insulated windows rotates relative to the anode workpiece at the same rotation speed, and moves toward the anode workpiece at a constant feed rate. All the convex structures on the anode workpiece can be machined at the same time by using a single tool electrode. There is no need to change tool electrodes and working stations during CRECM. This can significantly improve the machining efficiency.

Due to the unique structures and movements of the electrodes, the CRECM process is quite different from conventional sinking ECM. Thus, it is necessary to make feasibility studies on this ECM process. Computer simulation is an effective and low-cost method to predict the anode shaping process, and it has been successfully used in other studies. Numerical methods in computer simulation include the finite difference method, the finite element method (FEM), the boundary element method (BEM), and the finite volume method (FVM). In a computer numerical controlled ECM process, simulation was introduced to solve process planning, parameter optimization, and control problems.[11] Software for computer-aided engineering was developed to solve the direct and inverse problems of shaping by electrochemical generating machining (ECGM).[12] The use of the BEM in modeling of simple milling and turning features has been described,[13] and the three-dimensional ECM of the letter "E" was described elaborately.[14] The FVM has been developed for simulations of flow in complex geometries.[15] Furthermore, the FEM was selected to predict the anodic dissolution process and identify the etching behavioral trends under different parameters during the through-mask electrochemical micromachining process.[16] The eroded size during the fabrication of gas turbine blade turbulated cooling hole in ECM was determined using the FEM, and the results showed good agreements between the predicted and experimental results.[17]

Because of the more complex movements than those in the linear feed ECM process, the numerical simulation of the CRECM process is more complicated. In this paper, the simulation process is on the basis of the FEM. A mathematical model is established and the detailed simulation algorithm is developed according to electric field theories and the kinematic equations of the electrodes. An experiment is conducted to verify the validity of the simulation process. It is shown that the proposed simulation process is valid for convex shaping prediction and feasibility studies of the CRECM process as well.

2. Mathematical model

In this paper, analysis of the physical model is simplified, and the following assumptions are made: (1) the electrodes are defined as equipotential surfaces; (2) the current density distribution on the anode surface is dominated by ohmic effects; (3) the concentration of the electrolyte is assumed to be uniform during the whole process; and (4) the electrolyte flow within the inter-electrode gap is assumed to be ideal, with the electrical conductivity κ being approximately equal to a constant value. To reduce computation during the simulation, a portion of the arc segment of the anode workpiece that contains a convex structure is selected for study, as shown in Fig. 1. Points O and O_1 represent the centers of the anode workpiece and the cathode tool, respectively, and Oxy represents the workpiece coordinate, which is set absolute during the simulation process.

The distribution of the electric potential φ in the electrolyte domain Ω satisfies the Laplace equation:[18]

$$\nabla^2\varphi = 0 \tag{1}$$

As the whole process takes place in a reactor that is made of a PVC material, boundaries Γ_{13}–Γ_{16} are electrically insulated from the electrolyte. Furthermore, the additional anode and cathode surfaces are set to be insulated in order to correspond with the actual process. The interior walls of the cathode window are also insulated to decrease the influence of stray current attack during processing. Therefore, the boundary conditions are as follows:

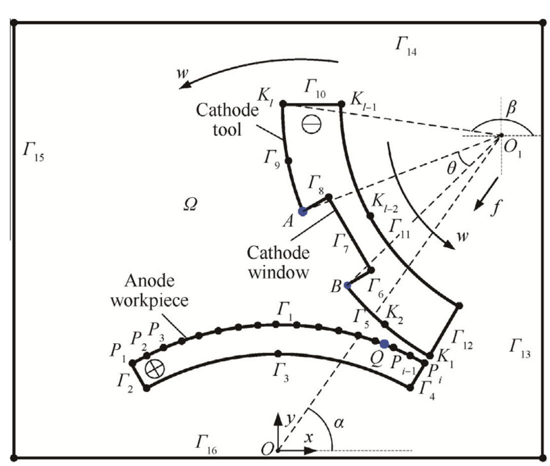

Fig. 1 Simplified physical model of the electric potential domain.