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Counter-rotating electrochemical machining of a combustor casing part using a frustum cone-like cathode tool

Dengyong Wang*, Zengwei Zhu, Bin He, Di Zhu, Zhongdong Fang

Nanjing University of Aeronautics and Astronautics, Nanjing, 210016, People's Republic of China

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ABSTRACT

An aero-engine casing is a thin-walled revolving part with many complex convex structures on its outer surface. It is usually made of difficult-to-cut materials such as nickel-based super alloy or titanium alloy, and may have a material removal ratio as high as 60–80%. Thus, manufacturing aero-engine casings via conventional machining methods is time-consuming and expensive. In this paper, a frustum cone-like cathode tool is used to manufacture a combustor casing part via counter-rotating electrochemical machining (CRECM). A mathematical model based on the CRECM process is established. A cathode design method is proposed based on optimizing the edge points of the concave window. The methods used to determine the three main frustum cone-like cathode tool parameters: the radius, the half cone angle, and the concave window angle, are described in detail. An experiment is performed using the frustum cone-like cathode tool in which a combustor casing part with complex convex structures is successfully machined. The surface is smooth and contains no flow tracks or rib-like remnants. Convex structures with various shapes can be fabricated using a single frustum cone-like cathode tool. The edges of the convex structures are trenchant and the dimensions of the machined convex structure meet the tolerance requirements. This indicates that the proposed CRECM process offers a superior machining ability to manufacture hard-to-machine combustor casing parts.

1. Introduction

Aero-engine casings are among the most important aero-engine components. They can be used for connection, load bearing, support and containment. The wall thickness of a casing part is usually 2–3 mm, but some areas are as thin as 1 mm. There are many convex structures with complex shapes on the outer surface of a casing. The material removal ratio associated with manufacturing an engine casing part can be as high as 60–80%. To achieve higher thermal efficiency, the engine casing is usually made of a difficult-to-cut material such as a nickel-based super alloy or titanium alloy. This kind of material usually has low heat conductivity coefficient, high hardness, high cutting force and large elastic deformation. Thus, manufacturing these parts is a significant challenge for traditional machining methods due to long processing cycles, high machining costs, and significant machining deformation. Bolsunovskiy et al. [1] reported that the machining productivity and surface location accuracy were limited by vibrations that arise when milling thin-walled parts. Scippa et al. [2] claimed that using conventional milling processes to maintain dimensional accuracy and straightness can be difficult due to the low stiffnesses of thin-walled parts. In particular, the turning tests investigated by Leone et al. [3] showed that machining a nickel-based alloy involves considerably higher forces and more severe tool wear than machining steel. In contrast, electrochemical machining (ECM) is a non-contact machining process that can effectively remove materials regardless of their hardness, as reported by Klocke et al. [4]. There is virtually no tool wear, machining stress, or plastic deformation in ECM [5]. Thus, it is a cost-effective method of machining thin-walled casing parts.

Fig. 1 shows the principle of conventional sinking ECM. A pre-shaped blocky cathode tool is generally used, and moves towards the anode workpiece at a constant feed rate. With high-speed electrolyte flows out from the inner cavity of the cathode tool, the anode material is dissolved rapidly, and the surface of anode workpiece with desired shape can be finally fabricated. However, when conventional sinking ECM is used to manufacture aero-engine casing parts, a series of pre-shaped blocky tool electrodes have to be prepared so that convex structures can be fabricated individually. Sheng et al. [6] used eight blocky tool electrodes to machine an aero-engine casing using as many as fifteen stations. There were flow-tracks and rib-like remnants remaining on the machined surface due to tool replacements and electrolyte inlets. The process required to achieve the desired machining quality was time-consuming and expensive. To solve these problems, a

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* Corresponding author at: Nanjing University of Aeronautics and Astronautics, 29 Yudao Street, Nanjing, 210016, People's Republic of China.
E-mail address: dywang@nuaa.edu.cn (D. Wang).

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Nomenclature

Notations

a	Radius of major axis of the projection of the cathode tool (mm)
α	Tilt angle of the cathode tool (°)
b	Radius of minor axis of the projection of the cathode tool (mm)
β	Half angle of the concave window (°)
β_{best}	Optimized concave window angle (°)
d	Width of the target convex structure (mm)
D_O	Initial center distance (mm)
E_i	Error between each point on the motion trail and the target one (mm)
$Error_{aver}$	average error between motion trail and target convex profile (mm)
$Error_{allow}$	Allowable error (mm)
G_e	End gap (mm)
G_s	Side gap (mm)
G_{i0}	Initial inter-electrode gap (mm)
N	Number of points selected on the motion trail
R_{0h}	Initial radius of anode workpiece in cross-section $Z=h$ (mm)
R_a	Bottom radius of anode workpiece (mm)
R_{ah}	Final radius of the anode workpiece at cross-section $Z=h$ (mm)
R_A	Distance between point A and center point O_1 (mm)
R_c	Bottom radius of cathode tool (mm)
R_{ch}	Radius of cathode tool at cross-section $Z'=h'$ (mm)
θ_a	Half cone angle of the anode workpiece (°)
θ_c	Half cone angle of the cathode tool (°)
v	Cathode feed rate (mm min^{-1})
w	Angular velocity (rad min^{-1})

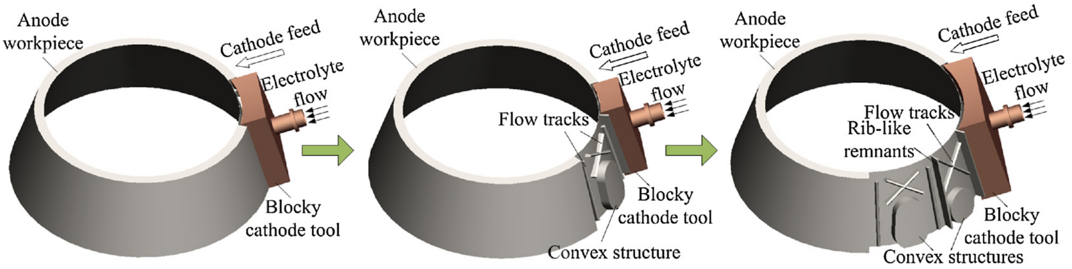

Fig. 1. Principle of the conventional sinking ECM process.

new ECM technology, counter-rotating ECM (CRECM), was proposed by Wang et al. [7]. In CRECM, the convex shaping process is simulated using the finite element method. The results confirm that the CRECM process is a feasible approach to fabricating convex structures on a thin-walled revolving part. In CRECM, the cathode tool used is a frustum cone-like part unlike in conventional sinking ECM.

In ECM, the shape of a tool electrode must be specially designed to obtain a workpiece with the desired shape. The cathode tool design problem has been investigated by many researchers. Early in the 1970s, Tipton [8] pioneered the cos θ method of cathode design. The distance between the workpiece and the cathode tool was assumed to be inversely proportional to cos θ. This method is valid for small values of θ. Lawrence [9] developed a modification of the cos θ method by calculating equipotential lines with small potential differences starting from the equilibrium anode shape. The flux lines between adjacent equipotential lines were assumed to be straight. In addition, various numerical analyses have been applied to the cathode design problem. Narayanan et al. [10] used a boundary element method to solve the inverse problem of predicting the tool shape. Three different formulations were tested to update the cathode boundary position. A simplified model was studied by Zhou and Derby [11], and a new cathode design formulation was developed using the finite element method. Sun et al. [12] proposed an approach that used the finite element method to design ECM tools for turbine blades. The results showed that this method could be used to design three-dimensional freeform surface tools. Kozak et al. [13] developed computer-aided engineering software to solve the inverse problem for electrochemical generating machining. The software could determine the tool electrode motion and trajectory needed to obtain the required workpiece shape. Lu et al. [14] solved the two and three-dimensional steady-state ECM tool design problem by transforming it into a shape optimization problem.

In CRECM, the design of cathode tool is essential to produce convex structures with the required accuracy. However, due to the unique shape of the cathode tool, the cathode design methods used in conventional ECM are not suitable for CRECM. In this paper, a frustum cone-like cathode tool was designed to machine a combustor casing part. A mathematical model was developed, and a cathode design method was proposed based on optimizing of the edge points of the concave window. The three main frustum cone-like cathode tool parameters: the radius, the half cone angle, and the concave window angle, were determined. An experiment was performed using the resulting cathode tool. The results show that the proposed cathode design method is effective in controlling CRECM machining accuracy, and that CRECM process is favorable method of manufacturing aero-engine casing parts.

2. Principle of the CRECM process for a combustor casing part

2.1. The mechanism of CRECM

The application of CRECM process to manufacture a combustor casing part is shown in Fig. 2. Unlike the blocky cathode tool used in conventional sinking ECM, the cathode tool used in CRECM is a frustum cone-like part. Concave windows with various shapes are designed on its outer surface. The combustor casing part is worked as an anode, and the frustum cone-like cathode tool is worked as a cathode. The anode workpiece and cathode tool counter-rotate at the same angular velocity. The cathode tool moves simultaneously towards the anode workpiece at a constant feed rate. With a high-speed electrolyte flushes the inter-electrode gap from the side, the shapes of the concave windows are gradually printed on the surface of the anode workpiece via electrolysis. As the cathode feed proceeds, the wall thickness of the anode workpiece becomes thinner. As a result, convex structures with specific heights are fabricated. Compared with conventional sinking ECM, the whole CRECM process is uninterrupted by using only a single frustum cone-like cathode tool, and there will be no rib-like remnants caused by tool replacements. In addition, a lateral flow pattern designed for the electrolyte can avoid producing flow tracks on the corresponding areas of