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Tube electrode high-speed electrochemical discharge drilling using low-conductivity salt solution

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ABSTRACT

Film cooling holes are widely used in the aerospace industry, and their fabrication requires high machining speed and accuracy, as well as good surface quality. Tube electrode high-speed electrochemical discharge drilling (TSECDD) is a promising hybrid machining method for the fabrication of film cooling holes in difficult-to-machine superalloys. An electrochemical reaction can occur if a low-conductivity salt solution is used in the drilling. Materials can also be removed at a high speed using electrical discharge machining (EDM). Thus, TSECDD and electrochemical machining (ECM) can be combined into a unique machining process using a low-conductivity salt solution. This machining process achieves both a high machining speed and good surface finish. In this study, the material removal mechanism of TSECDD was studied using a low-conductivity salt solution, and comparisons with high-speed electrical discharge drilling were made. The performance of the process was investigated using salt solutions of various conductivities. The results show that there are different material removal mechanisms in the frontal gap and the lateral gap and that, in the latter, there is a transition from EDM to ECM. Experiments conducted using TSECDD confirm that the use of this process with a low-conductivity salt solution can improve the machining surface and machining efficiency achieved. The results also show that the use of a low-conductivity solution improves the material removal rate, the hole diameter, and the taper angle.

1. Introduction

Micro-holes have a wide range of applications in the fields of aerospace, electronics, and miniaturized medical equipment. In the aerospace industry, turbine vanes and blades are required to operate at turbine inlet temperatures higher than the melting point of the metals currently used in gas turbine engines [1]. Advanced film cooling technology has been introduced in high-efficiency gas turbines to protect the vanes and blades from overheating. In film cooling, cooling holes that are distributed over the surface of a blade supply coolant air to form a thermal insulation film on the blade's external surface, thereby decreasing the incident convective heat flux on the surface. Modern gas turbine rotor and stator assemblies may have more than 20,000 small-diameter film cooling holes made in superalloys [2]. Successful fabrication of such micro-holes is essential to improving the capabilities of turbine engines.

Aero-engine components make wide use of nickel-based superalloys, titanium alloys, single-crystal alloys, and other difficult-to-machine materials that cannot be machined effectively with conventional processes [3]. Thus, the efficient machining of large numbers of film cooling holes in turbine blades presents a significant challenge. In addition, advances in the design of turbine engines are placing more rigorous demands on the surface quality of these holes. It is essential that the machined surfaces be free of the recast layers and microcracks that are usually generated by thermal machining [4].

Electrical discharge machining (EDM) is one of the most efficient machining processes for conductive materials [5]. The process, based on electro-thermal erosion of metallic materials, can be used with any difficult-to-machine metal material regardless of its density, toughness, or hardness [6]. During the machining process, there is negligible cutting force and no direct contact between the workpiece and the electrode. 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 [7]. In contrast, electrochemical machining (ECM) relies on the mechanism of anode electrochemical dissolution to remove material [8], with the advantage that the machined surface has no recast layers and is free of residual stress and microcracks [9].

Electrochemical discharge machining (ECDM), which is a hybrid of EDM and ECM, exploits the advantages of these two

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processing technologies, and given its machining efficiency and ability to achieve high surface quality, shows promise for use in the production of film cooling holes. Recently, ECDM has attracted increasing research interest [10]. Nguyen et al. [11,12] have proposed a process called simultaneous micro-EDM and micro-ECM (SEDCM), in which EDM and ECM are performed in sequence to improve the surface finish and machining accuracy using low-resistivity deionised water, a low feed rate, and short voltage pulses. Kurita and Hattori [13] have developed a new complex machining technology involving EDM and ECM-lapping, in which EDM shaping and ECM finishing are performed alternately in the same process, resulting in greatly improved surface roughness. Chung et al. [14] have investigated a finishing process for micro-hole surfaces machined by micro-EDM and have successfully obtained a finished surface using ECM in deionised water. Zeng et al. [15] have reported on a study of combined micro-EDM and micro-ECM milling of three-dimensional metallic microstructures, in which micro-EDM shaping and micro-ECM finishing were carried out successively on the same machine tool with the same electrode but using different machining media. De Silva et al. [16] have developed a hybrid of EDM and ECM called electrochemical-erosion sinking (ELESIN) that is employed together with associated process control and power systems and have found that surface quality and dimensional accuracy can be improved by properly controlling the process.

The greatest challenges in developing a drilling process for film cooling holes are the requirements of high machining speed and high surface quality. A process for fabricating film cooling holes at high speed without producing recast layers and cracks was investigated in this study. The process, tube electrode high-speed electrochemical discharge drilling (TSECCD), is an innovative combination of high-speed electrical discharge drilling and ECM. The two crucial components of TSECDD are the use of a tube electrode and the use of a low-conductivity salt solution. The combination of the two allows high-speed internal flushing of a low-conductivity salt solution. As a result, TSECDD offers advantages over other machining processes, such as EDM, ECM, and simultaneous EDM and ECM, in both the machining speed and surface quality achieved.

Unlike conventional ECDM for non-conductive materials [17], TSECDD is intended for use in the machining of difficult-to-machine superalloys. In contrast to high-speed electrical discharge drilling and SEDCM, the TSECDD technique combines electrochemical dissolution and electrical discharge erosion using a salt solution of extremely low conductivity rather than deionised water. Such a solution is effective in not only facilitating high-speed EDM but also enhancing electrochemical dissolution, which makes it possible to machine film cooling holes with high efficiency and good surface quality. In contrast to the cylinder type of electrode used in conventional EDM, ECM, and SEDCM, the tube electrode used in TSECDD achieves better high-speed inter-flushing, which enhances the machining efficiency of TSECDD. Hence, in this machining approach, the use of low-conductivity salt solution and a tube electrode are the two crucial components. In this study, the mechanism of TSECDD was examined, and the optimal conductivity of the working fluid, in terms of process efficiency, machining accuracy, and surface quality, was determined. Finally, the superiority of TSECDD over other processes with respect to machining speed and surface quality was confirmed.

2. Principles of TSECDD

2.1. The mechanism of TSECDD

TSECDD is a hybrid of ECM and EDM, with electrochemical dissolution and electrical discharge erosion occurring in the same process. Fig. 1 illustrates the mechanism of TSECDD. The discharge gap has a theoretical maximum value d_0 of approximately 10–20 μm. The gap must remain below d_0; otherwise, sparks cannot be maintained, and the EDM process will stop. Let the frontal gap be denoted by d_f and the lateral gap by d_l. The mechanism can be described in three distinct stages.

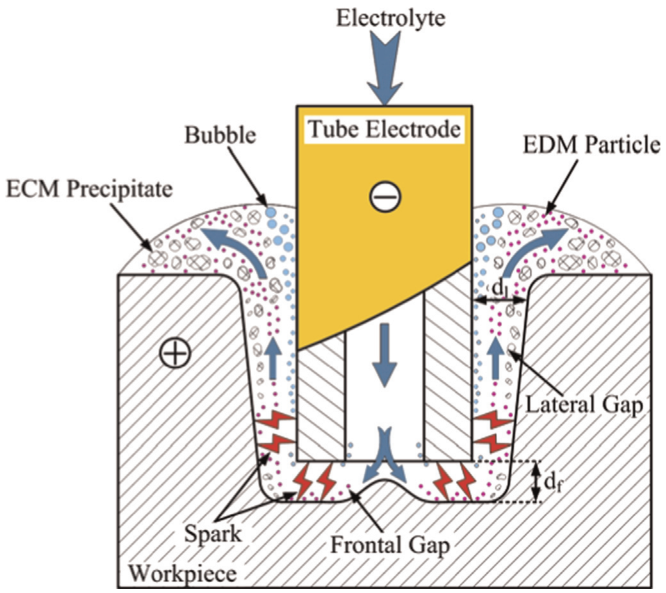

Fig. 1. Mechanism of tube electrode high-speed electrochemical discharge drilling.

Stage 1. $d_f \le d_0$ and $d_l < d_0$. As Fig. 1 shows, sparks occur at the forward part of the electrode, where the inter-electrode gaps, i.e. the frontal gap and the lateral gap, are smaller than the theoretical maximum discharge gap. In these regions, the effect of electrochemical dissolution is relatively slight, and anodic material removal depends more on EDM. Hence, the machining gaps rapidly enlarge around the forward part of the electrode. In the frontal gap in particular, discharge erosion allows a high feed rate to be achieved.

Stage 2. $d_f \le d_0$ and $d_l = d_0$. Here, the lateral gap is at the critical maximum value. Under these conditions, electrical discharge occasionally occurs as a result of process instability, and ECM begins to play a dominant role in material removal, with mass hydroxide precipitates and bubbles being generated in the lateral gap. This stage can be seen as a transition from EDM to ECM in the lateral gap, with machining in the frontal gap still mainly depending on EDM.

Stage 3. $d_f \le d_0$ and $d_l > d_0$. Here, the lateral gap exceeds the critical value, and EDM stops completely in that region. The lateral gap formed after EDM has finished is considered to be the initial gap for material dissolution, and the rough surface generated by EDM is removed by electrochemical dissolution in the lateral gap. Therefore, this stage is one in which EDM in the frontal gap and ECM in the lateral gap occur simultaneously.

In summary, the whole process can be considered as ECDM. In the frontal gap, EDM is always taking place, while in the lateral gap, the material removal mechanism transforms from EDM to ECM. The hole is drilled at high speed by EDM in the frontal gap, with the rough surface resulting from EDM being removed by ECM in the lateral gap. In this process, a low-conductivity salt solution, which is a bi-characteristic fluid, plays a crucial role, not only ensuring that EDM can take place in the frontal gap but also facilitating the electrochemical reaction in the lateral gap. To obtain