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Micro-drilling in ceramic-coated Ni-superalloy by electrochemical discharge machining

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ABSTRACT

Thermal barrier coating has been applied in turbine blades and vanes to improve the combustion temperature and thus the thermal efficiency. However, the fabrication of film cooling hole in the components with thermal barrier coating is challenging because the physical and chemical properties of each layer are quite different. Electrochemical discharge machining (ECDM) is a promising machining method for the fabrication of film cooling hole in these multi-layer materials. The gas film formed around the electrode, which acts as the dielectric during the machining, makes it possible for the ECDM to machine both electrical conductive and non-conductive materials. In this study, the current waveforms for the machining of both the coating and the superalloy substrate were investigated. It showed that only the electrochemical discharge exists during the machining of the coating. However, when machining the superalloy substrate, both the electrochemical discharge and the electrical discharge take place. Analysis of the experimental results revealed that the electrical discharge is the main factor to make the material on the superalloy substrate remove, while the electrochemical discharge results in a small secondary material removal on the machined surface. The surface roughness on the hole sidewall for the coating and the superalloy substrate were measured to be Ra 10.2 μm and Ra 5.6 μm, respectively. The thickness of recast layer on the machined surface of the superalloy substrate is 15 μm.

1. Introduction

In the aerospace industry, advanced film cooling technology has been widely used in high-efficiency gas turbines to obtain extremely high turbine inlet temperatures, subsequent high efficiencies, and longer life parts, as reported by Bunker (2005). Wang et al. (2010) reported that the aero-engine components are usually made of the difficult-to-cut materials, such as the nickel-based superalloys, titanium alloys and so on, which cannot be machined effectively by the conventional processes. Thus, there is a great demand in developing an effective fabrication technology for cooling holes.

Abbas et al. (2007) pointed out that electrical discharge machining (EDM) is one of the most efficient machining processes for conductive materials, especially for the difficult-to-cut metal material. 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 components mechanical capabilities as reported in detail by Lee and Tai (2003). Zhu et al. (2010) employed electrochemical machining (ECM) technology to fabricate cooling holes in turbomachinery components. They found that the major advantages of applying ECM are the production of smooth, stress- and crack-free surfaces. Zhang et al. (2015) proposed a hybrid machining of EDM and ECM for film cooling hole drilling. The hybrid machining is carried out in low-conductivity salt solution and materials are removed by both the electrical discharge erosion and electrochemical dissolution. Film cooling holes with high machining efficiency and good surface quality have been achieved by this hybrid machining.

Thermal barrier coatings, which are usually made of ceramics, have been introduced in turbine blades and vanes to improve the combustion temperature and thus the thermal efficiency, as reported by Meier and Gupta (1994). The structure and properties of thermal barrier coatings were reviewed by Padture et al. (2002). These ceramic-coated components consist of the non-electrical conductive material (the coating layer) and the electrical conductive material (the parent material). Therefore, ECM, which is limited to the machining of electrically conductive materials, cannot be applied to machining of ceramic-coated components. Mohri et al. (1996) realized the machining of insulating ceramics by EDM with an assisting electrode. A metal plate or metal mesh is arranged on the surface of ceramic insulator as an assisting electrode. However, it is challenging to machine thermal barrier coatings by EDM because of curved surfaces of turbine blades and vanes.

In order to machine the ceramic-coated components, Thoe et al.

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(1999) employed combined ultrasonic machining and EDM to drill small diameter cooling holes in ceramic coated nickel alloy. Ultrasonic machining was used to penetrate the ceramic coating and EDM was applied to machine the nickel alloy substrate with ultrasonic assistance. They found that it was possible to maintain the integrity of any intermediate bonding layers by adjusting the operating parameters during the transition from ceramic to nickel machining. Klocke et al. (2014) reported that the combination of EDM drilling and laser ablation in a single machine is intended for applications in film cooling hole machining in ceramic-coated component. Laser ablation is used for removing the thermal barrier coating and then EDM drilling is conducted for machining the parent material. However, the above hybrid machining processes are complex and the cost for the machine tools is high. Laser processing is an effective technique for multilayer material drilling. Corcoran et al. (2002) developed a laser drilling technique to generate cooling holes in multi-layer systems for use in the aerospace industry. Horn et al. (2000) achieved drilling in ceramic-coated nickel superalloy by melt extraction with pulsed laser radiation. Sezer et al. (2009) investigated a novel technique enabling to drill through thermal barrier-coated materials without delamination. However, when drilling with laser processing, the machining cost is high.

Wüthrich and Fascio (2005) reviewed that electrochemical discharge machining (ECDM), based on the electrochemical discharge phenomena around the tool electrode, is a low cost and flexible non-traditional machining technology. The alkaline electrolyte solution is the general solution used in ECDM and a gas film around the electrode is produced when the machining begins. The gas film plays a role as the dielectric and makes the discharge between the electrode and the electrolyte solution available, thus, ECDM overcomes the limitation on the electrical conductivity of the workpiece and both the electrical conductive and non-conductive materials can be machined by ECDM. Bhattacharyya et al. (1999) investigated the machining of non-conductive ceramic materials by ECDM. Peng and Liao (2004) studied ECDM technology for slicing non-conductive brittle materials. Khairy and McGeough (1990) have applied ECDM for shaping small shallow dies in conductive metal.

In the previous study, Zhang et al. (2015) proposed an electrochemical discharge drilling technique using low-conductivity salt solution for the cooling hole drilling in difficult-to-cut superalloys. Electrical discharge machining (EDM) and electrochemical machining (ECM) can be combined into a unique machining process using the low-conductivity salt solution. However, no complete gas film formed when using the low-conductivity salt solution and the non-conductive materials cannot be machined. In this paper, an alkaline electrolyte solution with high conductivity was used in ECDM and a complete gas film can be formed around the tool electrode. ECDM was applied to machining film cooling hole in ceramic-coated nickel superalloy for the first time. Unlike the cylinder type of electrode used in conventional ECDM, a helical electrode was chosen as the tool electrode. This helical electrode combines the mechanical material removal in electrochemical discharge machining of the coating layer. In addition, the flutes along the electrode body facilitate the electrolyte refresh in the machining zone. In this study, the current waveforms during the machining of both the coating material and the parent material were investigated. The machined surfaces on different layers of the cooling hole were also studied.

2. Experimental design

2.1. Experimental setup

The experimental setup is mainly composed of a three-axes micro-EDM machine integrated with an additional ECDM processing device, as shown in Fig. 1. The three axes of the micro-EDM machine, all driven by linear motors, have a move resolution of 0.1 μm. A spindle, whose radial runout is within 1 μm during rotation, is fixed on the *Z*-axis to clamp and rotate the tool electrode. The ECDM processing device includes a processing cell and a pulsed power supply. In the conventional ECDM for the non-conductive material machining, as shown in Fig. 2(a), an auxiliary electrode is used. In this paper, as the parent material of the workpiece is conductive, therefore, no auxiliary electrode was used. Details of the circuit connection were shown in Fig. 2(b), the cathode is connected to the tool electrode, the anode is directly connected to nickel-based superalloy. During the ECDM process, the current signals were measured and gathered by using a current probe which is connected to an oscilloscope.

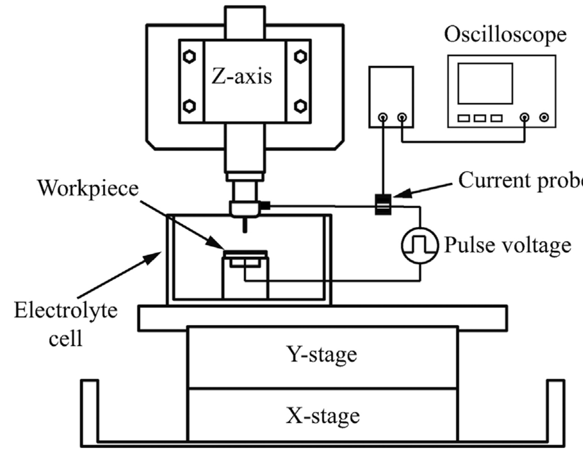

Fig. 1. Experimental setup.

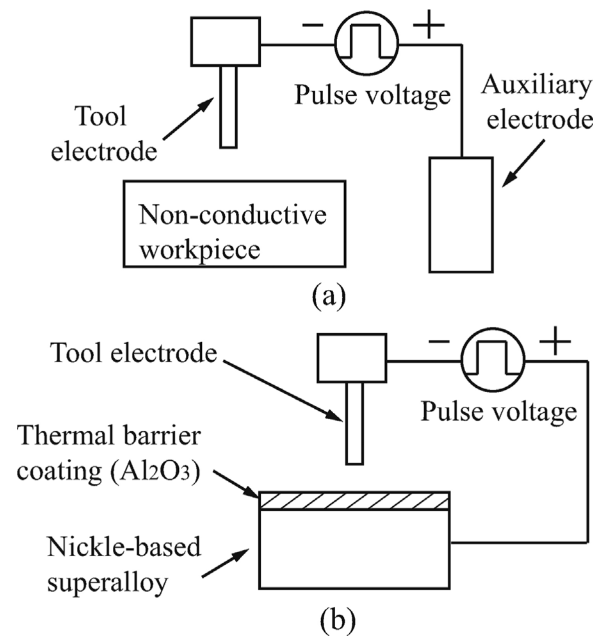

Fig. 2. The circuit connection. (a) Circuit connection in conventional ECDM. (b) Circuit connection in this paper.

2.2. Material

The tool electrode used in the experiments is the general micro-drill bit made of tungsten carbide. Fig. 3 shows the shape and dimensions of micro-drill bit. The small end with drill flutes is the working area. Previous studies show that ECDM using a micro-drill bit improves the material removal rate by 65% due to the improvement of electrolyte flushing through the drill flutes, as reported by Wei et al. (2010) and Razfar et al. (2014). As can be seen from Table 1, the electrode shows properties of low electrical resistivity, high melting point and hardness. The high melting point enables the drill bit to withstand the high