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Experimental research on electrochemical machining of titanium alloy Ti60 for a blisk

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Abstract Ti60 (Ti–5.6Al–4.8Sn–2Zr–1Mo–0.35Si–0.7Nd) is a high-temperature titanium alloy that is now used for important components of aircraft engines. Electrochemical machining (ECM) is a promising technique that has several advantages, such as a high machining rate, and can be used on a wide range of difficult-to-process materials. In this paper, orthogonal experiments are conducted to investigate ECM of Ti60, with the aim of determining the influences of some electrochemical process parameters on the surface roughness. The most important parameter is found to be the frequency of the pulsed power supply. It is found that using suitably optimized parameters for ECM can greatly decrease the surface roughness of a workpiece. A surface roughness of approximately 0.912 μm can be obtained with the following optimal parameters: NaCl electrolyte concentration 13wt%, voltage 20 V, pulse frequency 0.4 kHz, duty cycle 0.3, temperature 23 °C, and anode feed rate 0.5 mm/min. Furthermore, blisk blades have been successfully processed using these optimized parameters.

1. Introduction

Electrochemical machining (ECM) is a nontraditional machining process that is used to machine extremely hard materials that are difficult to cut with conventional machining methods.[1,2] ECM generates no burr and no stress, and provides a long tool life, with a damage-free machined surface, a high material removal rate, and good surface quality.[3–5] The ECM process was originally developed for manufacturing complex-shaped components in the defense and aerospace industries, and has been extended to many other industries such as manufacturing of automotive and surgical components, forging of dies, and, more recently, miniature manufacturing.[6,7] ECM of new composite materials has recently been investigated.[8–10]

In ECM of titanium alloy, defects such as pitting and poor surface roughness often appear. In addition, a passivation film is easily produced during ECM,[11–15] leading to a high decomposition voltage. Furthermore, the electrolytic products from ECM mostly form an insoluble floc, which easily adheres to the surface of the anode, resulting in differences in dissolution behavior between the substrate and anode surfaces. Therefore, it is difficult to obtain good surface quality in ECM of titanium alloy. Clifton et al. investigated the surface characteristics and integrity of γ-TiAl subjected to ECM using perchlorate and

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chloride electrolytes. Large areas of grain boundaries appeared on the surface, which were generally of high integrity with no evidence of structural defects.[16] Dhobe Shirish et al. conducted experiments on ECM of commercially pure titanium using a sodium bromide electrolyte (20 g/L) at a tool feed rate of 0.1 mm/min. The roughness of the oxide-layered machined surface was in the range of 2.4–2.93 μm, suitable for use in titanium implants without the need for further surface preparation.[17] Qu et al. reported the use of wire ECM with axial electrolyte flushing to machine titanium alloy (TC1). The machining parameters were optimized by Taguchi experiments using sodium chloride and sodium nitrate electrolytes.[18] Zaytsev et al. proposed optimal conditions for ECM of Ti–6Al–4V titanium alloy with a microsecond pulsed current, under which there appeared to be neither surface-layer hydrogen nor pitting.[19] Klocke et al. found slightly more rapid dissolution of the α-phase in a detailed cross section, with a higher magnification showing a slight waviness – but without any rim zone – of the surface for Ti–6Al–4V.[20]

It is clear from the above results that different processing parameters are often applied to different titanium alloys. There have been very few studies of ECM of the new titanium alloy Ti60 (Ti–5.6Al–4.8Sn–2Zr–1Mo–0.35Si–0.7Nd), which is of particular interest for aerospace applications. Therefore, this study investigates the effects of electrolyte concentration, applied voltage, pulse frequency, duty cycle, electrolyte temperature, and feed rate on surface roughness, and optimizes the process parameters. Finally, blisk blades with good surface finish are fabricated.

2. Experimental procedure

In order to obtain good surface finish, an ECM system and a machining fixture are required. In addition, the appropriate levels and factors of the orthogonal experiment are very important.

2.1. ECM system

The ECM system is very complex. To guarantee the reliability of each test, the stability of the machining process parameters, such as electrolyte temperature, electrolyte flow rate, concentration, and spindle motion accuracy, must be ensured.

Therefore, in this system, the temperature deviation of the clean electrolyte is controlled within ±0.5 °C using a heat exchanger. In ECM, the flow rate of the clean electrolyte is controlled by a programmable logic controller. The large amount of electrolytic products from ECM are stored in a second electrolyte tank. To ensure a clean inflow of electrolyte, the electrolyte in this tank is filtered into the clean electrolyte tank through a frame filter every few minutes. If the volume of the electrolytic products is significant after a few months, the frame filter press will be run, in order to compress the electrolytic products into pieces. The pulsed power supply and the movement of the spindle are controlled by an independent system. The ECM device used in these studies is shown in Fig. 1.

2.2. Machining fixture

During ECM, a workpiece moves toward the cathode, which is stationary. The cathode and the connecting rod for the anode are made out of stainless steel. A schematic of the machining fixture is shown in Fig. 2. The workpiece is Ti60 with heat treatment of 1050 °C/2 h air cooled followed by 700 °C/2 h air cooled. The workpiece is cylindrical with a diameter of 20 mm. Before the ECM test, to remove the oxide film on the surface of the workpiece, its end surface is polished. The workpiece is shown in Fig. 3.

The machined surface roughness is measured using a surface roughness tester with an accuracy of 0.01 μm and a resolution of 0.001 μm (Perthometer Mahr1, Germany). The main components on the surface after ECM are detected using a scanning electron microscope (SEM, Hitachi S3400N, Japan).

2.3. Orthogonal experiment design

In ECM, an oxide film is easily produced on the surface of the titanium alloy.[18] As the thickness of the oxide film increases, the surface roughness becomes worse. However, the oxide film thickness can be reduced by using a halide electrolyte, which has a high activation ability. The ranking of activation ability for some commonly used ions is: $Br^- > Cl^- > I^- > ClO_3^- > NO_3^- > SO_4^{2-}$. At the same time, the equipment corrodes easily with NaBr or KBr electrolyte. Therefore, NaCl is the most suitable electrolyte. In these experiments, a concentration in the range of 4wt%–16wt% is applied for NaCl electrolyte.

Because a high electrode potential is used in ECM of titanium alloy, the process parameters are relatively large. A voltage range of 20–40 V and a temperature range of 23–55 °C are used in the experiments. In addition, the pulsed power supply enables timely removal of the product during the intermittent machining time in ECM. Therefore, a pulsed power supply is necessary, and it must have sufficient time to remove the floc product. The frequency and duty cycle of the pulsed power supply are 0.2–1.0 kHz and 0.2–0.6, respectively. Feed rates in the range of 0.2–0.6 mm/min are used after trial-and-error determination.

In this study, an appropriate $L_{25}(5^6)$ orthogonal array is applied. The six machining parameters and five levels are shown in Table 1. Twenty-five experiments are performed.

3. Presentation of results

The experimental parameters and results are shown in Table 2. Additionally, each experimental result is tested twice to increase the reliability of the tests.

The range analysis in Table 3 shows that the preferred scheme is $A_2B_1C_2D_2E_1F_4$, and a verification test is conducted. The specific parameters and the experimental results are shown in Table 4. Fig. 4 shows the influences of machining parameters on surface roughness. The impact of each factor on the surface roughness will be described in the following subsections.

3.1. Effect of electrolyte concentration on surface roughness

As shown in Fig. 4(a), the surface roughness improves (i.e., decreases) as the concentration increases in the range of 4wt%–13wt%. This is because the higher the electrolyte concentration is, the stronger the activation is. Then, the oxide film will have very little effect on ECM as the concentration increases. The dissolution of the elements in the alloy will be uniform, and the surface roughness is better. However, when