Inconel 718, a nickel-based superalloy widely used in the aviation field, is difficult to machine using traditional methods such as milling. Electrochemical machining (ECM) is a recommended manufacturing method for Inconel 718 due to its effective and economical processing characteristics. This paper investigates the dissolution effects on surface integrity in ECM of Inconel 718. Two types of materials with different heat treatments, solid solution, and solution and aging were studied to analyze their electrochemical behavior. They have different metallographic microstructures and precipitate phases. There are many Laves phase (Fe2Nb), δ phase (Ni3Nb), and carbides in material of solid solution state, while there are fewer in material of solution and aging state. Experiments were then performed on these materials under identical ECM conditions. The results show that the surface roughness of the solid-solution material was about Ra 1.378 μm while it was Ra 0.188 μm for the solution and aging material. A dissolution model was proposed to illustrate the electrochemical behavior of solid solution Inconel 718, revealing that the uneven distribution of the metallographic phase and the rich content of the element niobium (Nb) will influence the surface integrity of the ECMed sample.

Many investigations have also been undertaken on Inconel 718 in ECM. Mount et al. derived an analytical expression for the current-time transient, considering a number of parameters and verified the expression for Inconel 718 using a planar tool and workpiece configuration.27 Huang et al. researched the electropolishing behavior of Inconel 718 in perchloric–acetic mixed acids with different concentrations of HClO4.28 Klocke et al. measured the effective material-removal rates of Inconel 718 and examined the surface properties of the rim zone.8 Wang et al. researched the electrochemical dissolution behavior of Inconel 718 at low current density in NaNO3 solution and obtained a current efficiency curve.29 Wang et al. studied the ECM property of two laser rapid formed Inconel 718 alloys in both as-deposited and solution-annealed states and found that the dissolved surface quality is better in solution-annealed state.30 Guo et al. studied the electrochemical removal of different phases from laser solid formed Inconel 718. The results showed that Nb-rich γ phase dissolved faster than γ matrix phase, and the detachment rates of the different phases were different with the increase of current densities.31–33

To date, most reported research has focused on the ECM of Inconel 718 with relatively normal current densities, solutions, material-removal rates, etc. Some investigations were performed on the electrochemical behavior of Inconel 718 formed by additive manufacturing. The research reveals that the macrostructure of a metal influence its dissolution in ECM, causing different surface appearances on the machined samples. However, little work has been done on anodic dissolution of Inconel 718 formed by forging with different heat treatments. This paper investigates the dissolution effects of forging Inconel 718 with different heat treatments and these materials have different microstructures. In this contribution, the influence of the microstructure and the distribution of alloying elements on the electrochemical dissolution behavior of Inconel 718 is studied.

Materials and Experimental Methods

Materials.—Two types of Inconel 718 with different heat treatments were used in the experiments. One was in solid solution state, the other was in solution and aging state. Their chemical components, microstructure, and morphology were measured to analyze their material characteristics.

The chemical compositions of these two materials were detected by an electron microprobe (SPECTROMAXx, SPECTRO, Germany) and they were relatively close to each other (Table I). The main components were nickel (Ni), iron (Fe), and chromium (Cr), and their mass fractions were 50.5%, 21.46% and 18.61% in material No.1 and they...
were 52.1%, 19% and 19.15% in material No. 2. These three elements constituted about 90% of the alloys.

In addition, a hardness tester (HXS-1000AK, CANY, China) was used to measure the hardness of these two materials. After measurement, the hardness in solution state was about HRC 26, while it was HRC 42 in solution and aging state. The hardness of the material in solid solution state was lower than that in solution and aging state.

Furthermore, the microstructure and morphology were measured with a metallographic microscope (200MAT, ZEISS, Germany) to observe the distribution of the grain size, precipitation quantity, and grain boundary state, etc. After these measurements, metallographical figures for the two types of Inconel 718 were obtained (Fig. 1). The microstructures of these two materials were significantly different. (1) The grain sizes of material No. 1 (solid solution state) were not uniform and their distribution was uneven. Meanwhile, the boundaries of the grains were not very clear. However, the grain distribution of material No. 2 was relatively uniform and the sizes were comparatively similar. The boundaries were relatively distinct. (2) There were many white substances in material No. 1 and they were surrounded by black matter. In order to analyze these substances, further measurements were conducted using energy dispersive spectroscopy (EDS, XFlash Detector 5010, Bruker, Germany). After detection, the chemical composition of the white substances (point A) was obtained (Fig. 2a). They were rich in Nb and there were many carbides in the same place. The phase of the white substance may be the Laves phase. In addition, the chemical composition of the black substances (Point B) was also measured (Fig. 2b). There is still a lot of Nb compared with the substrate and the phase of the black substance may be the precipitated δ phase. These white and black areas may be generated because of the large amount of the element Nb. (3) There was also some carbon at both point A and point B. This carbon always exits as carbides in Inconel 718. The aggregation of Laves phase and carbides phase were generated in the solidification of Inconel 718. Therefore, the white substance at point A contains Laves phase and carbides, while the black substance at Point B contains δ phase and carbides. (4) There are fewer black areas (like Point B’) and white areas (like Point A’) at the grain boundary in material No. 2 (solution and aging state) than in No. 1 (Fig. 1b). These differences in the microstructures of the two materials may affect their dissolution characteristics in ECM.

**ECM experiments.**—ECM experiments were performed on the two materials under the experimental conditions shown in Table II. A specific set-up was designed to observe the different machining effects. As shown in Fig. 3, a cubic specimen, whose size was 30 × 30 × 10 mm, was embedded in a square groove in a stainless steel base. The cathode was mounted on a rod and the workpiece installed on an anode terminal that could move forward toward the cathode at a certain feed-in rate. The flow channel was designed to be sealed within a fixture and its width was narrow enough to ensure a sufficient flow rate. In the process, the electrolyte flows into one side of the workpiece and exits from the other side. The electrolyte inlet was arranged at the top of the fixture while the electrolyte outlet was at the bottom. After several minutes, the current remained stable for a period, indicating that the process reached an equilibrium state. The experiment was then stopped.

After the experiments, the surface roughness of the machined specimen was detected by a roughness tester (M1, Mahr, Germany) to analyze the surface quality in a microscopic view. The micromorphology was then measured using a scanning electron microscope (SEM, S-3400N, Hitachi, Japan). In addition, the elements of the product were detected by EDS to analyze the precipitation law of the products. Finally, the affected regulation in ECM was obtained for these two different crystal phases of Inconel 718 by observing the microstructure of the machined surface after ECM.

**Results and Discussion**

**Surface roughness analysis.**—The machined surfaces of the two types of material after the ECM process are shown in Fig. 4. The
Electrolyte inlet
Electrolyte outlet
A
Ammeter
Power
Feed
Fixture
Thermometer
Guage
Filter
Valve
Pump
Electrolyte cell
Workpiece
Anode terminal
Cathode terminal
Electrolyte inlet
Electrolyte outlet
(a)

Figure 3. Schematic of the experimental set-up, (a) machining system diagram, (b) real set-up.

Table I. Chemical composition of two types of Inconel 718.

| No. | C  | Si  | Cr  | Ni  | Mo  | Nb  | Ti  | Al  | Co  | B  | Fe  | Mass fraction (%) |
|-----|----|-----|-----|-----|-----|-----|-----|-----|-----|----|-----|------------------|
| 1   | 0.05 | 0.10 | 18.61 | 50.5 | 3.06 | 4.78 | 0.91 | 0.42 | 0.11 | 0.004 | balance |
| 2   | 0.052 | 0.07 | 19.15 | 52.1 | 2.93 | 5.02 | 0.98 | 0.57 | 0.12 | 0.005 | balance |

Five places on the machined surfaces of the two specimens were detected by using the roughness tester. Then the surface roughness was obtained, as shown in Fig. 4. The roughness values are illustrated in Table III. The average surface roughness of No. 1 is about $Ra_{1.378 \mu m}$, while it is about $Ra_{0.188 \mu m}$ for No. 2. The results show that the surface quality of No. 2 is much better than that of No. 1.

Microtopography analysis.—To analyze the ECM effects of these two materials, the microtopographies of the specimens were also measured. The microstructures of the machined surfaces were obtained using SEM (Fig. 5). The surface was not smooth and there were many gray products with irregular shapes on specimen No. 1 (Fig. 5a). The reason for this phenomenon is the non-uniform dissolution of the material and the precipitated phase at the boundary being rich in the element Nb on the workpiece before the ECM process (Fig. 1a). However, the microtopographical surface of specimen No. 2 was on the whole very smooth, and there were fewer and smaller gray products on the surface than on specimen No. 1. The dissolution of the workpiece was uniform, which is consistent with the crystal phase of No. 2. The grain of material No. 2 was even and there were fewer black areas because it contains little elemental Nb. In short, the microstructures of Inconel will affect its machining quality in ECM.

Table II. Experimental conditions.

| Parameters                     | Conditions        |
|--------------------------------|-------------------|
| Cathode feeding rate $v_c$ (mm/min) | 0.5               |
| Electrolyte                    | NaNO$_3$         |
| Inlet pressure $P_i$ (Mpa)      | 0.8               |
| Outlet Pressure $P_o$ (Mpa)     | 0.15              |
| Electrolyte temperature $T$ (°C)| 30±0.5            |
| Electrolyte conductivity $\kappa$ (Ω$^{-1}$m$^{-1}$)| 15.2              |
| Electrolyte concentration      | 20%               |
| Voltage $U$ (V)                | 20                |
| Pulse duty                     | 70%               |
| Pulse frequency $f$ (Hz)        | 1000              |
| Initial inter-electrode gap (mm)| 0.3               |

Table III. Surface roughness of the two specimens (unit: $\mu$m).

|                        | 1   | 2   | 3   | 4   | 5   | Average |
|------------------------|-----|-----|-----|-----|-----|---------|
| No.1                   | 1.277 | 1.473 | 1.6 | 1.187 | 1.351 | 1.378   |
| No.2                   | 0.194 | 0.188 | 0.204 | 0.191 | 0.165 | 0.188   |

Electrochemical dissolution analysis of Inconel 718.—In the electrochemical dissolution, the workpiece dissolves because the oxidation reaction occurs at the anode. The metal elements in the anode lose electrons and are oxidized during the process. As shown in Table I, there were several chemical components in Inconel 718 and the contents of nickel (Ni), chromium (Cr), iron (Fe), niobium (Nb), molybdenum (Mo), and titanium (Ti) were much greater in the alloy. Therefore, the reactions of these elements are the main
consideration in this paper, whereas the contents of aluminum (Al) and cobalt (Co) are so small in the alloy that their reactions in the process are neglected. According to the electrochemical reaction principle, the standard electrode potential of these main elements and their anodic dissolution reactions during ECM, as described in the literature, are shown in Table IV.37

Normally, the lower the standard electrode potential, the easier it is to lose electrons from the metal. Those elements with a lower standard electrode potential are the first to undergo a chemical reaction in ECM. In Inconel 718, the standard electrode potentials of Nb and Ti are $-1.1$ and $-1.63$ V, respectively, much lower than those of Ni, Cr, Fe, or Mo. This regulation shows that the dissolution rate of Nb-rich phase should be higher than the matrix due to its more negative electrode potentials and be dissolved first in the process, whereas there are many precipitated products containing Nb, C, and Ti (Fig. 6b), especially a larger content of the element Nb. The dissolution phenomenon does not agree with a single element dissolving in ECM. This may be because there are many carbides in the white substance at point A and in the black substance point B. These carbides are non-conductive and they are insoluble in the process.
Figure 6. SEM and EDS of the two specimens.

Figure 7. Sketch of the electrochemical dissolution behavior of Inconel 718 in solution state (a) Initial stage, (b) dissolution stage.

**Table IV. Standard electrode potential of the main elements in Inconel 718.**

| Anodic dissolution reaction | Standard electrode potential (V) |
|-----------------------------|-------------------------------|
| $Ni \rightarrow Ni^{2+} + 2e^{-}$ | $0.25$ |
| $Cr \rightarrow Cr^{3+} + 3e^{-}$ | $0.74$ |
| $Fe \rightarrow Fe^{2+} + 2e^{-}$ | $0.44$ |
| $Nb \rightarrow Nb^{3+} + 3e^{-}$ | $1.0$ |
| $Mo \rightarrow Mo^{3+} + 3e^{-}$ | $-0.2$ |
| $Ti \rightarrow Ti^{2+} + 2e^{-}$ | $1.63$ |

The electrochemical dissolution behavior for Inconel 718 in NaNO$_3$ solution is considered to involve two stages, as depicted in Fig. 7. First, the gradual dissolution of the matrix material of Inconel 718 with the step-by-step exposure of the insoluble particles. After a period of dissolution, more and more material around the insoluble particles is dissolved. The interaction between the insoluble particles and the matrix material is insufficient to resist the mechanical stress of the high flow rate electrolyte. The insoluble particles in the white and black substances begin to detach from the matrix material. Therefore, there are some bumps on the machined surface and a significant amount of elemental carbon in the bumps, especially in Fig. 6b. Wang and Guo also found that the surface products of ECMed Inconel 718 in NaNO$_3$ solution contained insoluble substances such as Nb carbide (NbC) and oxides of Nb.

However, there were fewer precipitated products containing Nb, C, or Ti in the material No. 2 sample after ECM (Fig. 6b), because the amounts of elements such as Nb are small and there were fewer carbides in the material. The entire surface then dissolves evenly in the process. Combining SEM with the surface roughness in Table III, the surface quality is better when the content of Nb in Inconel 718 is low and the crystal phase of the material is smooth. This reveals that uniformity of the microstructure and fewer black areas rich in Nb in the material can improve the surface quality after the ECM process.

**Fabrication of complex blades for application.**—These two materials were chosen to fabricate a complex blade for application. The experimental conditions were the same as the aforementioned
conditions. After processing, samples were obtained and they are shown in Fig. 8. As shown in the figure, the surface appearance of blade 1, machined using material No. 1, is rough while it is very smooth for blade 2, which used material No. 2. To observe the surface clearly, the surface is magnified with a microscope (Fig. 9). The machined surface of blade 1 is pitted and it looks like a burned surface. However, the surface of blade 2 is bright and the grains are obvious. As mentioned above, the reason for the different machining effects of the blades is the difference in the material microstructure. The uneven distribution of the metallographic phase and the rich content of the element Nb will reduce the surface integrity of the ECMed blade. The results further reveal that the microstructure influences the machined surface of complex components in the ECM process.

Conclusions

This paper investigated the dissolution effects of Inconel 718 with two types of treatments that were solid solution state and solution and aging state. These two types of materials have different metallographic microstructures and precipitate phases. There are many Laves phase, δ phase and carbides in material of solid solution state, while there are fewer in material of solution and aging state.

Experiments were performed on these two types of materials under identical ECM conditions. The results show that the surface roughness of the material of solid solution state was about Ra 1.378 μm whereas it was Ra 0.188 μm of the material of solution and aging state. In addition, there were many more gray products generated on the machining surface on former material than on latter material.

A dissolution model was proposed to illustrate the electrochemical behavior of solid-solution Inconel 718 in NaNO₃ solution. It reveals that uniformity of the microstructure and amounts of the precipitated phase at the boundary areas where rich in Nb can influence the surface quality after the ECM process. Furthermore, two aero-engine blades were fabricated using these two types of materials for application. The results reveal that the surface roughness in ECM can be enhanced by improving the microstructure and the Inconel 718 with solution and aging state is better for ECM.

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