J Appl Electrochem (2010) 40:525–532
DOI 10.1007/s10800-009-0024-y

ORIGINAL PAPER

Investigation on the flow field of W-shape electrolyte flow mode in electrochemical machining

Dong Zhu · Di Zhu · Zhengyang Xu · Qing Xu · Jia Liu

Received: 26 May 2009 / Accepted: 25 September 2009 / Published online: 10 October 2009

Abstract A new W-shape electrolyte flow mode was developed to improve the blade accuracy and surface quality in electrochemical machining. Its mathematical model in the interelectrode gap was obtained as equations of such main flow parameters as the pressure, channel width, volumetric gas-phase concentration, velocity, and temperature. According to the model, the distribution of the flow field was simulated. Subsequently, experiments were carried out so as to validate the W-shape electrolyte flow mode and its mathematical mode. The results proved that the mathematical model was correct, the flow mode was reasonable, and the accuracy and surface quality of blade were enhanced greatly.

Keywords Flow field · Electrochemical machining · Blade · Pressure · Cathode

1 Introduction

Electrochemical machining (ECM) is a non-contact, electrochemical dissolution process that is used to shape the anode metal, namely the workpiece. Figure 1 illustrates the basic principle of ECM process. During the ECM, the low voltage is applied between the electrodes by power supply. The cathode, namely the tool, is normally moved toward the anode at constant feed rate. And the electrolyte transferred by centrifugal pump from electrolytic cell flows at high speed through the gap to carry away the dissolved metal. By ECM, electrically conductive materials, regardless of their hardness and toughness, can be machined. Workpieces, with smooth, burr, and stress-free surfaces, can be produced. Recently, ECM has been widely applied in aeronautics, aircraft and aerospace, molds and dies, and some other industries. However, further application of ECM has been limited due to difficulties in cathode design, process monitoring and control, and disposal of machining products [1–6].

There are many process variables that may affect product quality. Datta and Landolt [7] analyzed the effects of the thermal field and flow field on the efficiency of the ECM process. To improve flow field in the gap of ECM, Fan et al. [8] has developed a magnetic field system in which the magnetic flux perpendicularly cuts flow line. Xu et al. [9] presented a flexible 3-electrode feeding method in ECM to machine the profile and the platform of the turbine blade. This feeding method was favorable to the stability of the machining process and could enhance the accuracy and surface quality of the blade. But the block electrodes it used could not feed into the channel of the parts, such as the integral impeller, to machine the blade (Fig. 2). Therefore, some new method needs to be developed to meet the requirements.

Sheet electrode, a new cathode, is designed to feed into the channel of integral impeller and machine the blade in ECM. When the new electrodes (including blade basin electrode and blade back electrode) feed into the channel, a W-shape channel is formed. Whether the flow field in the channel is good or not will directly affect the machining surface quality and processing stability so its analysis becomes important. According to the continuity equation, momentum equation, thermodynamic equation, and Blasius formula, the characteristics of flow field in the interelectrode gap are analyzed by numerical analysis software. Six

D. Zhu (✉) · D. Zhu · Z. Xu · Q. Xu · J. Liu
College of Mechanical and Electrical Engineering,
Nanjing University of Aeronautics and Astronautics,
210016 Nanjing, China
e-mail: zhudong@nuaa.edu.cn

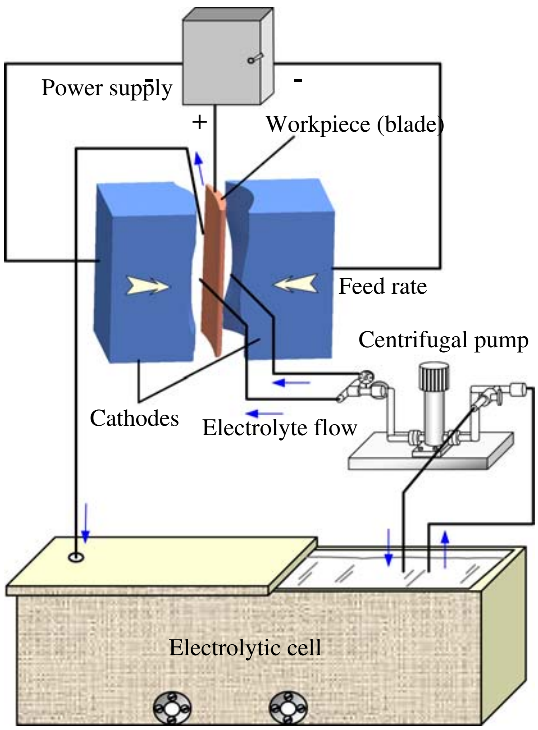

Fig. 1 Principle of electrochemical machining

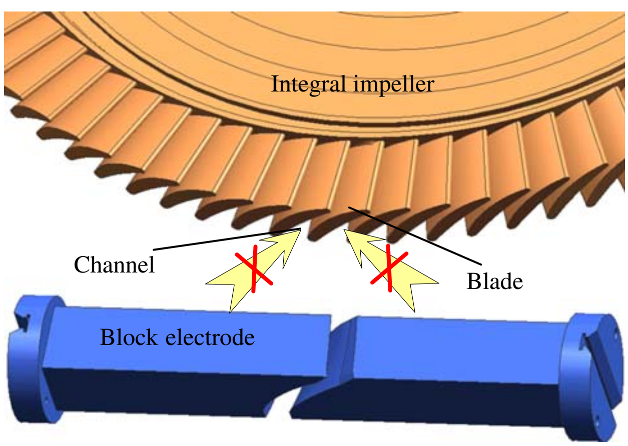

Fig. 2 Block electrodes to machine integral impeller

parameters are taken into account in the direction of the motion: machining gap, electrolyte temperature, electrolyte velocity, viscous shear stress, electrolyte pressure, and bubble rate. Furthermore, the pressure distribution is simulated by the fluid analysis software. The consequence shows that the pressure on both sides of the electrode is partially counteract and its difference values are low. It also proves that the new flow mode can keep the feeding of the electrode stable in the process and ensure both the uniformity and the stability of the flow field in the machining area. In order to evaluate the rationality of the new flow field, a relevant clamping fixture is designed and

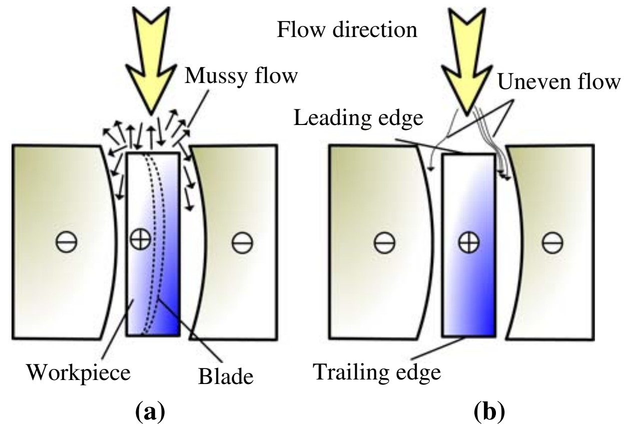

Fig. 3 Problems of lateral flow

necessary experiments are performed. The results indicate that the stability of the processing are well improved, the accuracy and surface quality of the samples are enhanced by using the new sheet electrodes and the W-shape electrolyte flow mode.

2 The W-shape electrolyte flow mode

In the process of machining blade in ECM, the electrolyte flow mode is generally the lateral flow mode (Fig. 3), the electrolyte enters into the channel from the leading (trailing) edge and exits from the trailing (leading) edge. The uniformity of this flow field is good and it is favorable for machining the profile of the blade. However, lateral flow mode has many disadvantages. As shown in Fig. 3a, when the electrolyte flows at a high speed (about 10–60 ms^{-1}) into the channels, it will be divided into two parts by the leading edge. Because the thickness ($\sim$5–10 mm) of the workpiece is much larger than the machining gap width (0.2–0.5 mm) and most electrolyte will collide with the workpiece, the flow field is turbulent, which will cause process instability, low surface quality, and even a short circuit between the cathodes and workpiece. Meanwhile, this flow mode has less controllability because of uneven flow rate passing through the blade basin and blade back (Fig. 3b). In addition, the fabrication of the clamping fixture is complicated and the fixture needs to seal both sides of the electrodes to prevent the electrolyte area from leaning.

To overcome these shortcomings, the axial flow mode is preferable (Fig. 4). Figure 4a demonstrates one type of axial flow mode in which the electrolyte goes into the channel from blade tip to root. The electrolyte is separated by workpiece into two flows, which is similar to lateral flow at this point, so the flow field is inhomogeneous and the machining accuracy is low at the tip position. Figure 4b

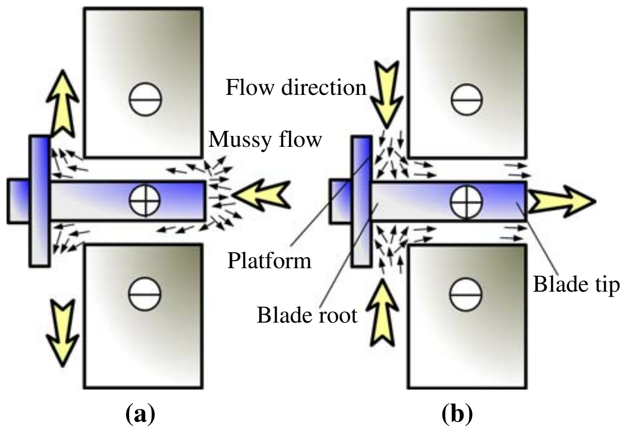

Fig. 4 Axial flow to machine single blade

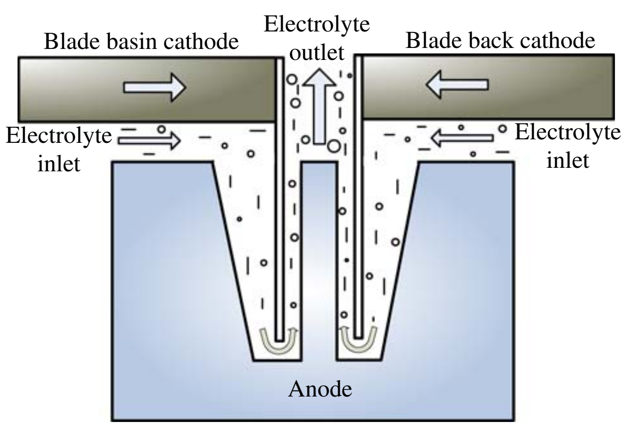

Fig. 5 The W-shape electrolyte flow mode

illustrates the other type of axial flow mode. In this mode, the electrolyte gets into the channel along the platform, changes direction at blade root, and outflows from the tip. It is divided into two parts to flow across blade basin and blade back separately. The flow rate of these two parts can be controlled, respectively. So the controllability of the flow field is good and the flow in the machining gap is uniform and stable. However, the flow is mussy and unstable at inlet, which has negative influences on the surface quality of samples. So the root where has low precision requirements is laid at this place. Nevertheless, the block electrode, adopted in this mode, cannot get into the channels because of its large thickness (Fig. 2).

In order to solve above-mentioned problems, a new sheet electrode is proposed to feed into the channel and a W-shape electrolyte flow mode is presented (Fig. 5). This kind of flow mode is of great help to improve the surface quality of the blade and it is proposed to machine such type of blade as integral impellers.

In this flow mode, the electrolyte gets into the channel along the electrode, passes by the blade root and body, at last gets back to the electrolytic cell from electrolyte outlet. Because the shape of the machining channel is just like the letter “W”, this new flow mode is called W-shape electrolyte flow mode. The workpiece is machined by the bidirectional feed with sheet electrodes, viz. the blade basin cathode and blade back cathode. The cathodes and the workpiece are placed on the same horizontal level. The workpiece is fixed and the sheet electrodes installed in the cathode fixture are moved toward the anode. The process is done in the sealed machining area formed by the cathodes, anode, and the clamping fixture. Various factors of the flow field are intercoupling and the situation in the channel is very complicated, especially the pressure on the sheet electrodes. It is necessary to analyze the characteristics of the fluid of this mode.

3 Theoretical models

3.1 Mathematical models of fluid field in ECM

The generation of the gas at the electrodes, particularly the cathodic hydrogen, and the dissolution of metal from the anode, means that the fluid in the machining gap in ECM is of a multi-phase, rather than a single-phase. In most investigations of fluid flow in ECM, only the gas bubbles are assumed to have appreciable effects on the nature of the flow, which therefore can be regarded as two-phase [10]. To simplify the problems, some assumptions about the two-phase flow need to be formulated combining with the actual conditions.

3.1.1 Two-phase flow assumption

The gas bubbles are well distributed in the fluid and the liquid phase is incompressible. The state change of gas phase obeys the state equation of ideal gas. There is no mass conversion between the gas and the liquid. The parameters of each phase are similar in every cross section along the flow channel.

3.1.2 Electric field assumption

Surfaces of the cathode and anode are equipotential. The potential perpendicular to the flow channel is linear distribution and the potential gradient is equal.

Besides these assumptions, the process is under the condition of steady state. The parameters of each phase are the position function not the time function when the processing is in a steady state. As machining proceeds, and with the simultaneous movement of the cathode at a typical rate, say 0.3 mm/s, toward the anode, the gap width along the electrode length will gradually tend to be a steady-state value.

On the basis of these assumptions and conditions, the flow fluid model in ECM is formulated, as Fig. 6 shows.

A mathematical model of the flow field is built. Parameters affecting the distribution of the gap, such as bubble rate, pressure, temperature, viscous shear stress, and liquid velocity are taken into account.

The mathematical equations can be obtained according to (1) the continuity equation for the conservation of mass, (2) the momentum equation of motion for the conservation of momentum, (3) the thermodynamic equation of state.

$$(1-\beta(x))\Delta(x)u(x) = \Delta_0 u_0 \quad (1)$$

$$\frac{p(x)}{R_g T(x)}\beta(x)\Delta(x)u(x) = \eta_g \kappa_g i x \quad (2)$$

$$\Delta(x)\frac{dp(x)}{dx} + p\frac{d\Delta(x)}{dx} + \rho_1 u_0 \Delta_0 \frac{du(x)}{dx} = -2\tau(x) - \eta_g \kappa_g i(x) \quad (3)$$

$$t(x) = t_0 + \frac{U_R i}{\rho_1 u_0 \Delta_0 C}x \quad (4)$$

where x is the length along the electrolyte flow channel, β the bubble rate, Δ the machining gap (channel width), Δ_0 the initial machining gap, u the electrolyte velocity, u_0 the electrolyte velocity at the inlet, p the electrolyte pressure, R_g the constant of the gas state of hydrogen, t the electrolyte temperature, η_g the current efficiency of the hydrogen evolution, κ_g the quality electrochemical equivalent, i the current density, ρ_1 the electrolyte density, τ the viscous shear stress, U_R the voltage, and C the specific heat capacity.

According to the shaping law in ECM, the formula for the machining gap can be obtained, considering the influence of temperature and the bubble rate on electrolyte conductivity in the process.

$$\Delta(x) = \frac{U_R \kappa_0}{i}[1 + \xi(t(x) - t_0)](1 - \beta(x))^n \quad (5)$$

Here κ is the electrolyte conductivity and ξ is the temperature coefficient of electrolyte conductivity. n is the index that considers the influence of the bubble rate on electrolyte conductivity. It can be chosen from 1.5 to 2 and is equal to 1.5 usually.

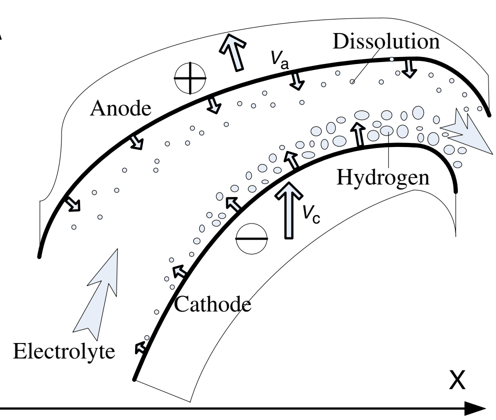

Fig. 6 The model of the machining gap in ECM

The Eqs. 1–5 reveal the flow field parameters and its distribution law of the machining gap in ECM. The independent variable is x and the flow field parameters $p(x)$, $\beta(x)$, $T(x)$, $\Delta(x)$, $u(x)$, $\tau(x)$ are the independent variables that need to be solved. The relationship between $\tau(x)$ and other functions can be obtained according to the amendment method of conversion coefficient of liquid phase and the Blasius formula.

$$\tau(x) = 0.0332\rho_1\left[\frac{(1-\beta(x))^3 u(x)^7 v}{\Delta(x)}\right]^{0.25} \quad (6)$$

where v is the kinematic viscosity coefficient. $\tau(x)$ is expressed as an explicit function in x, while the other parameters are the mutual implicit functions which contain differential equations. This article uses the fourth-order Runge–Kutta method with varying step size to solve these equations. The distribution map of the flow parameters along the flow channel can be drawn according to the machining parameters and the inlet boundary condition (Fig. 7).

As it shows in Fig. 7, (1) the air volumetric flow rate increases gradually in every cross section along the flow channel. The bubble rate β increases rapidly at the end of the channel outlet where its value is about 4.3%. (2) The medium temperature of the liquid-phase and the gas-phase increases linearly in the flow direction. (3) The electrolyte pressure decreases gradually in the direction of flow motion because of the fractional resistances on the channel wall. (4) The electrolyte velocity increases slowly along the flow direction with the increase of the bubble rate, and it increases much faster when the electrolyte is close to the

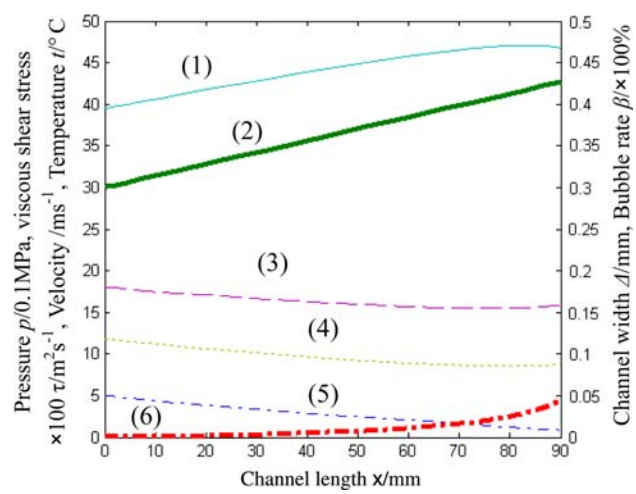

Fig. 7 The distribution map of the flow parameters along the flow channel. (*1*) Channel width (machining gap Δ), (*2*) electrolyte temperature t, (*3*) electrolyte velocity u, (*4*) viscous shear stress τ, (*5*) electrolyte pressure p, (*6*) bubble rate β

outlet. (5) The channel width (machining gap) increases appreciably then decreases gradually at the electrolyte exit. Its change, caused by the electrolyte conductivity variation induced by the comprehensive action of the temperature and bubble rate, is small and its fluctuation is homogeneous from the global aspect. The machining gap increases because of the rising of the conductivity caused by the elevation of the temperature at the inlet where the temperature influence is dominant. And it becomes small because of the decrease of the conductivity aroused by the rising of the bubble rate at the outlet where the bubble rate effect is dominant.

3.2 Characteristics of the parameters of liquid field

The electrolyte velocity and pressure play a very important role in the ECM process. They are important conditions ensuring the stability of the process.

3.2.1 The electrolyte velocity

The electrolyte velocity is the main flow parameter to ensure the stability of process in ECM. There are two functional requirements needed to be met before its determination.

1. The metal dissolution can be carried away fast and the flow is turbulent when the electrolyte velocity is at a high speed. It is beneficial to uniform the flow and eliminate the concentration polarization. The electrolyte velocity corresponding to the turbulent state should conform to the formula below:

$$u_{\mathrm{Re}} > 2300\frac{v}{D_{\mathrm{h}}} \tag{7}$$

where D_{h} is the hydraulic diameter.

2. The temperature rise can be controlled when choosing a high-speed velocity. The electrolyte velocity corresponding to the temperature rise should satisfy the following formula:

$$u_t = \frac{i^2}{\rho_1 \kappa_0 c(\Delta t)} L \tag{8}$$

The electrolyte velocity corresponding to the temperature rise is much higher than that corresponding to the turbulent state. So the temperature rise control is a major factor to determine the velocity.

3.2.2 The electrolyte pressure

Assumptions: The cross-section area at the inlet of the channel is much larger than that at the machining gap, so the velocity at the inlet is even smaller than that at the machining gap area. Compared with the velocity at the machining gap, the inlet velocity is close to 0 ms^{-1}. On the premise of the assumptions, the pressure at the inlet has three functions: (1) enhancing the flow kinetic energy in the machining gap, i.e., dynamic pressure, (2) overcoming the frictional resistance in the channel, (3) balancing the pressure at the electrolyte outlet, i.e., back pressure. The formula of the pressure at the electrolyte inlet can be obtained according to the Bernoulli equation and the Blasius formula

$$p_1 = p_u + p_v + p_2 = p_2 + \left(\alpha_2 + f\frac{L}{D_{\mathrm{h}}}\right)\frac{\rho_1 u^2}{2} \tag{9}$$

where p_1 is the inlet pressure of the machining gap, p_{u} the dynamic pressure of the flow, p_{v} the viscous friction, p_2 the back pressure at the outlet, α_2 the kinetic energy correction factor, usually $\alpha_2 = 1$, f the friction coefficient, and L the length of the machining gap.

The pressure simulation of the flow field in abovementioned mathematical model is obtained by the fluid analysis software. The exact vector graph of the electrolyte pressure on both sides of the electrode is achieved under this flow mode (Fig. 8). Conclusions drawn from Fig. 8 are as follows: (1) the pressure at the inlet is equal to 0.5 MPa approximately. Its value is the biggest here because the gap at the inlet is much wider than that at the machining area, (2) the pressure is a constant value which is equal to 0.5 MPa at the non-machining area, (3) the pressure at the corner begins to decrease because the gap becomes narrower, (4) the pressure in the machining gap decreases gradually and the outlet pressure is about 0.1 MPa.

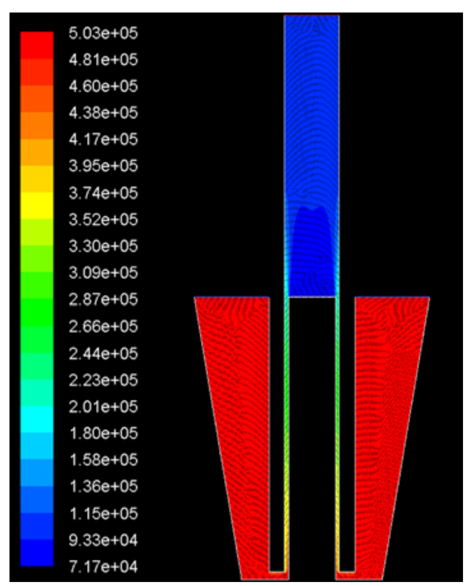

Fig. 8 The flow pressure vector graph

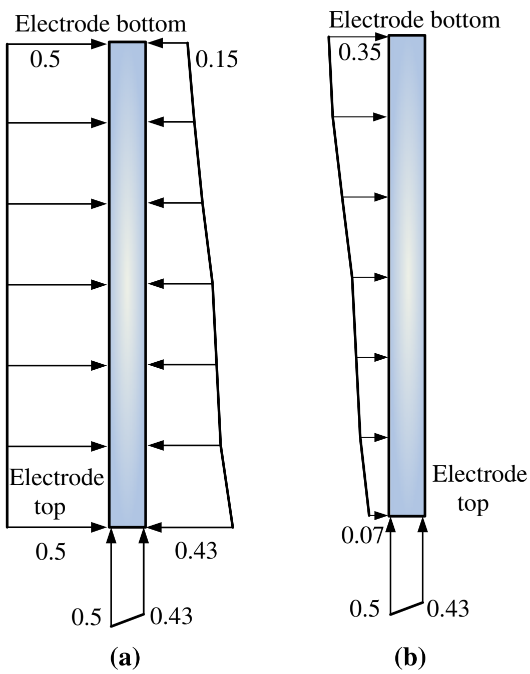

Fig. 9 The actual pressure (**a**) and pressure difference (**b**) on electrode

The value of the pressure in the channel is 0.5 MPa at inlet, while it decreases to 0.1 MPa at outlet. The actual pressure and pressure difference on the sheet electrode can be obtained (Fig. 9). Figure 9a shows that the actual electrolyte pressure in the non-machining channel is constant, whereas the values become gradually smaller and smaller from the top to the bottom of the electrode in the machining channel. Figure 9b shows the pressure difference on the electrode. The pressure difference decreases significantly after the pressure counteraction on the two sides of the cathode. This means that the differential value at the bottom is the largest and at the top is the smallest. The vibration caused by the pressure is generated most easily at the electrode top, but the pressure difference is the smallest there. So it can weaken the degree of the vibration. Vice versa, the differential value at the bottom (installation place) is the largest, while the vibration is least easy to produce. Therefore, the force condition on electrode is reasonable. Using this new electrolyte flow mode, the vibration of the sheet cathode is small and the cathode can feed stably in the process.

The pressure distribution of the new flow mode can be seen from above paragraphs, for comparison the normal axial electrolyte flow mode is also established (Fig. 10a). The electrolyte flows into the machining channel from the inlet and flows out of the gap from the outlet. The fixed end of electrode is at the electrolyte outlet. Then the pressure in the machining gap is obtained by the fluid analysis software. The pressure vector distribution in the gap is shown in the Fig. 10b. Figure 10b illustrates that the pressure at the inlet is 0.527 MPa and its value changes to 0.2 MPa near the outlet.

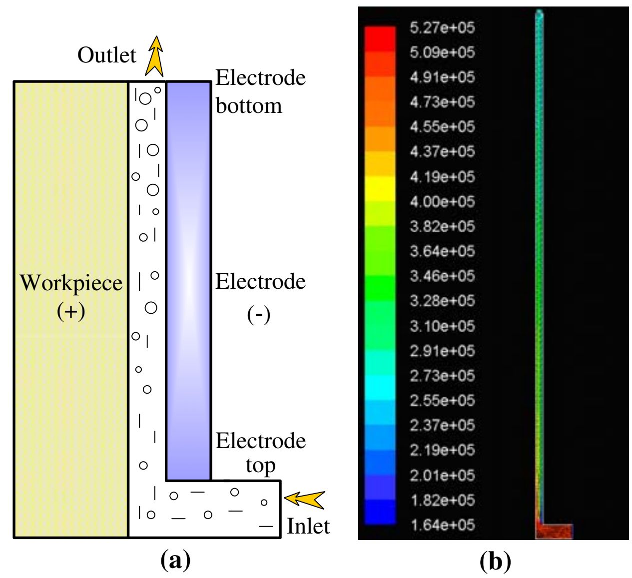

Fig. 10 Normal axial flow mode (**a**) in ECM of blade and its pressure distribution, **b** the electrolyte pressure vector graph

In order to obtain the influences of the pressure on the electrode, the deformation of the electrode is analyzed by the finite element analysis software. Figure 11 shows the electrode deformations of the normal axial and W-shape flow mode. Their figures indicate that the maximum deformation, occurs at the top of the electrode, is 0.218 mm in W-shape flow mode, while it is 0.409 mm in normal axial flow mode. Therefore, such conclusion can be

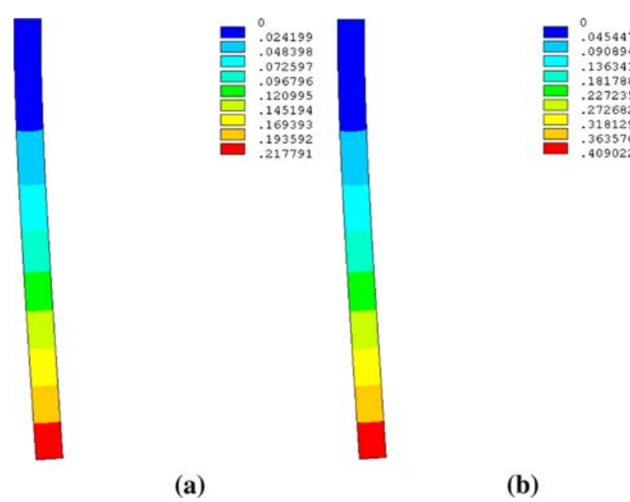

Fig. 11 Electrodes deformation in two electrolyte flow mode. **a** Deformation of W-shape electrolyte flow mode, **b** deformation of normal axial electrolyte flow mode

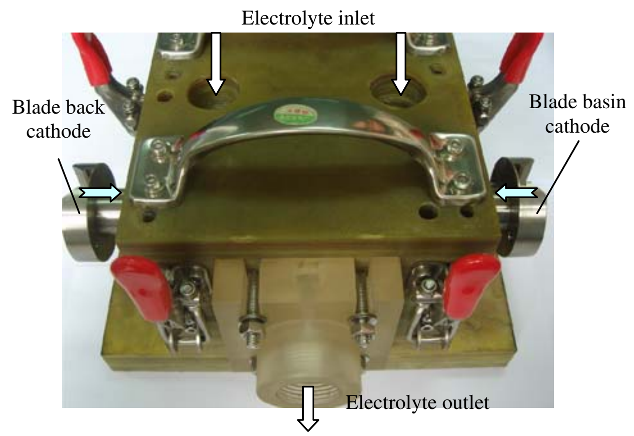

Fig. 12 The ECM fixture

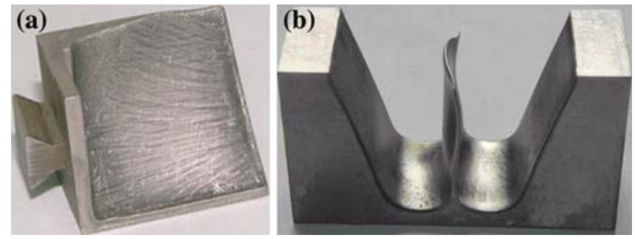

Fig. 13 Experimental samples

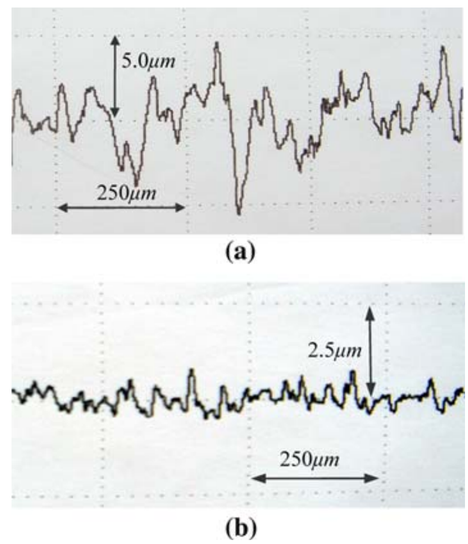

Fig. 14 Surface roughness of samples 1 (**a**) and 2 (**b**)

drawn that the deformation in the new flow mode is lower than that in the normal axial flow mode.

4 Experimental studies

In order to verify the feasibility of the W-shape flow mode and the uniformity and stability of the fluid, machining experiments are conducted on an industry-use ECM machine. The new ECM fixture made of epoxy materials is displayed in Fig. 12. As Fig. 12 shows, there are two electrolyte inlets on the fixture top and one electrolyte outlet at the front side. The cathode is made of stainless steel and the workpiece material is nickel base alloy. The blade basin cathode and the blade back cathode feed bilaterally to the workpiece, respectively, in the process.

The electrolyte is $NaNO_3$ and its temperature is 30 °C. The electrolyte at high speed flows through the channel by means of a multistage centrifugal pump. The power supply is a 15 V DC voltage. The cathode moves to the workpiece at the velocity of 0.3 mm min^{-1}. The electrolyte pressure at the inlet is 0.5 MPa and the back pressure is 0.1 MPa. Table 1 shows the machining conditions.

The experiments are conducted in the W-shape and normal axial flow mode separately under above-mentioned machining conditions. The initial shape of the blade blank is square block. Figure 13 shows two machined blade samples with complex surfaces. Figure 13a displays the sample 1 which is machined in normal axial flow mode. There is remarkable flow mark on the machining surface. Figure 13b demonstrates the sample 2 and there is no obvious flow mark on its surface. The roughness of the two samples is equal to 1.7 and 0.4 µm separately (Fig. 14). The result indicates that this new electrolyte flow mode is reasonable and the flow field and process is stable.

The change of the machining gap along the flow channel is obtained by examining the samples. Figure 15 shows the theoretical values and the experimental data of the steady machining gap. It indicates that the experimental gap increases gradually along the flow channel. The change trend between the theoretical gap and the experimental gap is basically identical. Figure 16 shows the deviation of the two gaps. The maximum deviation is 0.026 mm near the channel inlet and 0.024 mm near the channel outlet. The deviation close to the channel inlet and outlet is relatively large, because the flow field is not stable at these areas. The deviation is small at the middle area of the channel, because the flow is uniform at this place. Therefore, it proves that the mathematical model of the above-mentioned flow field built in this article is reasonable.

Table 1 Machining conditions in ECM

Voltage (V)	Electrolyte	Inlet pressure (MPa)	Back pressure (MPa)	Materials	Temperature (°C)
15	10% $NaNO_3$	0.5	0.1	Nickel base alloy	30

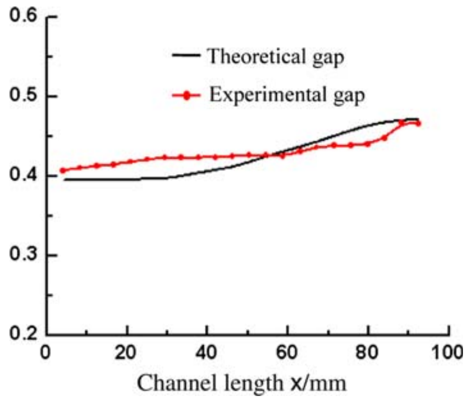

Fig. 15 The theoretical and experimental value of the machining gap along the flow channel

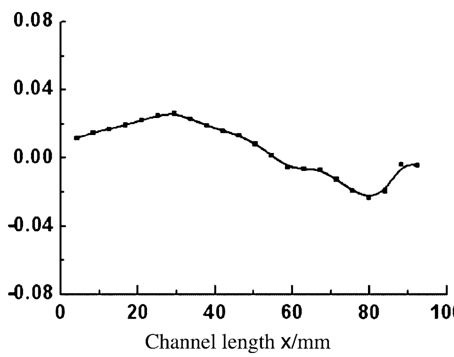

Fig. 16 The deviation of the theoretical and experimental value of the machining gap

5 Conclusions

In the machining process of ECM, the electrolyte flow mode directly affects the surface quality of the workpiece. Flow field factor is of great influence on machining workpiece, especially on machining complicated parts made from difficult-to-cut material, such as aero engine blades.

Under these circumstances, a new W-shape electrolyte flow mode has been proposed and its mathematical model is built in the article. To test their validity, the characteristics of electrolyte flow in the machining gap have been analyzed using numerical analysis software. Six parameters are studied along the flow channel. The electrolyte pressure is simulated by the fluid analysis software and the consequences show that the pressure differential values on the electrode are low. And the deformation of the electrode is smaller in W-shape flow mode than that in normal axial flow mode. Experiments of the blade in ECM have been performed and the results suggest that the mathematical model is consistent with the experimental results. The characteristics of the flow field and the stability of the process are well improved using the sheet cathode and the W-shape electrolyte flow mode. In addition, the surface quality is also improved and the unstable factors of the flow field are decreased.

Acknowledgments This article was supported by the Aviation Science Foundation of China (No. 04H52055) and Doctoral Degree Funds of Chinese Ministry of Education (No. 20050287020).

References

1. Chang CS, Hourng LW, Chung CT (1999) J Appl Electrochem 28:321
2. Zhu D, Rajurkar KP (1999) J Am Soc Mech Eng 10:589
3. Rajurkar KP, Zhu D, McGeough JA, Kozak J, De Silva A (1999) Ann CIRP 48(2):567
4. Rosenkracnz C, Lohrengel MM, Schultze JW (2005) Electrochim Acta 50:2009
5. Fan ZW, Hourng LW (2009) Int J Mach Tools Manufact 49:659
6. Bhattacharyya B, Munda J (2003) Int J Mach Tools Manufact 43:1301
7. Datta M, Landolt D (2000) Electrochim Acta 45:2535
8. Fan ZJ, Wang TC, Chen L, Liu C (2005) Proceedings of the China association for science and technology, China, vol 204, August
9. Xu ZY, Zhu D, Wang L, Shi XC (2007) Chin J Mech Eng 44(2007):189
10. McGeough JA (1974) Principles of electrochemical machining. Chapman and Hall, London