Research Journal of Applied Sciences, Engineering and Technology 3(9): 1007-1013, 2011
ISSN: 2040-7467

Submitted: July 20, 2011 Accepted: September 07, 2011 Published: September 20, 2011

3-D Flow Field of Cathode Design for NC Precision Electrochemical Machining Integer Impeller Based on CFD

[1,2]Rui Wu, [1]Danwen Zhang and [1]Juan Sun
[1]Department of Mechanical and Electrical Engineering, Luoyang Institute of Science and Technology, Luoyang 471023, China
[2]Collage of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

Abstract: In order to achieve high efficiency and low cost cathode designing, improve stability of process in NC precision electrochemical machining of integer impeller, a method of applying Computational Fluid Dynamics (CFD) to aid designing flow field structure of cathode and parameters for NC-ECM has been proposed in this study. The designing of flow field is the key point in cathode design and a suitable flow field design guarantees the process stability in electrochemical machining. A numerical model of the three-dimension flow field was built according to the geometrical model of interelectrode gap and cathode outline. Then the numerical simulation of 3-D flow field was performed by using the standard k-ϵ turbulence model when the turbulence state in electrochemical machining had been determined. The effect of cathode's structure and initial electrolyte pressure on the electrolyte flow field was analyzed according to the results of numerical simulation. A series of results similar to the actual experimental results are obtained. The method deduced in this paper could be used to achieve high efficiency and low cost cathode design, select of initial electrolyte pressure, and consequently a lot of "trial and error" cycles will be deduced.

Key words: Computational fluid dynamics, electrochemical machining, numerical control, simulation, 3-D flow field designing

INTRODUCTION

Because of their high strength, high temperature stability, and high corrosion resistance, high-strength and heat-resistant alloys, such as nickel-based superalloys, titanium alloys have found wider application than ever as aero-engine integral impeller materials, for which traditional machining methods of manufacturing integral impeller such as electro-discharge machining, die casting, forging and numerical control machining might result in poor surface quality, residue stresses and surface micro-cracks (Pajak *et al*., 2006; Wüthrich and Fascio, 2005; Peng and Liao, 2004).

In comparison with them, Electrochemical Machining (ECM), by using anodic dissolution to shape metal, has been developed to machine high-strength, heat-resistant alloys, which are otherwise extremely difficult to be worked by conventional methods, to which, naturally, ECM has turned to be the ideal alternative in aeronautic and astronautic industries, particularly in production of integral impeller. However, further application of ECM is limited by the difficulties in tool (cathode) design and process monitoring.

Numerical Controlled Electrochemical Machining (NC-ECM) is a new kind of technology which combined the advantages of Electrochemical Machining (ECM) with Numerical Control technology. Through years of research and testing, this technology is becoming mature. By using generating motion of simple cathode, this technology can solve the problems in machining complex-shaped components which are made of heat-resistant and high-strength alloys. Since 1985, Kozak *et al*. (1998, 2000), Ruszaj and Zybura-Skrabalak (2001) and Jiawen (2005) have done lots of studies on NC-ECM, now a day, NC-ECM plays an important role in machining of complex workpiece, integer impeller.

In process of NC-ECM, stabilization is as important as precision. The stabilization of NC-ECM has been affected by uniformity and stabilization of electrolyte's flow field during electrochemical machining. Further, the stabilization of electrolyte's flow field will be decided by the shape and structure of electrolyte's channel in cathode. So the cathode design methods have been studied by a great number of researchers all over the world. Hunt (1990), Bhattacharyya (1997) and Zhou (1995) have research some new methodes for cathode design. Chunhua *et al*. (2006) applied the FEM in cathode design. Chang *et al*. (1999), Chang and Houmg (2001) and Wu *et al*. (2008) introduced CFD for cathode design.

Corresponding Author: Rui Wu, Department of Mechanical and Electrical Engineering, Luoyang Institute of Science and Technology, Luoyang 471023, China

Nevertheless, these research results are not easily available to the industrial users and often not used friendly, and most of these researches are focus on two dimension flow field designing or electric field. As a result, the cathode design still relies much on the skills and experiences of the operators. In practice, the trial-and-error method takes repetitive machining runs to obtain the required cathode shape and structure.

In order to achieve high efficiency and low cost cathode design, the efficiency of cathode designing and improve stability of process in NC precision electrochemical machining of integer impeller, a method of applying Computational Fluid Dynamics (CFD) to aid designing flow field structure of cathode and parameters for NC-ECM has been studied in this paper. The designing of flow field is the key point in cathode design and a suitable flow field design guarantees the process stability in electrochemical machining. A numerical model of the three-dimension flow field was built according to the geometrical model of interelectrode gap and cathode outline. Then the numerical simulation of 3-D flow field was performed by using the standard k-ϵ turbulence model when the turbulence state in electrochemical machining had been determined. The effect of cathode's structure and initial electrolyte pressure on the electrolyte flow field was analyzed according to the results of numerical simulation. A series of results similar to the actual experimental results are obtained. The method deduced in this paper could be used to achieve high efficiency and low cost cathode design, select of initial electrolyte pressure, and consequently a lot of "trial and error" cycles will be deduced.3-D Flow field model of interelectrode gap. Figure 1 shows the cathode shape for NC precision electrochemical machining integer impeller. Its working face is a narrow and long rectangle plane, and the electrolyte flows out of the slot in working face at high speed and fills in the whole interelectrode gap. The size and shape of cathode have been limited by space between two adjacent vanes in order to avoid overcut during machining, and the result is that the electrolyte channel in cathode is small, as shown in Fig. 2. In order to ensure the uniformity and stabilization of electrolyte's flow field during electrochemical machining, the structure of electrolyte channel in cathode must be optimized.

The shape of electrolyte flow field during electrochemical machining is constituted of cathode outline, electrolyte channel in cathode, workpiece surface and interelectrode gap. Figure 3 shows a sketch of interelectrode gap during NC precision electrochemical machining integer impeller. The length of slot for electrolyte flow out of cathode is longer than that of vane, so that many electrolytes cannot flow into interelectrode gap and the outshoot of slot is one of outlets in electrolyte flow field.

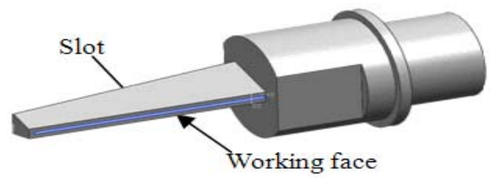

Fig. 1: Cathode shape

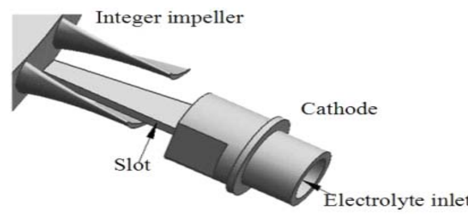

Fig. 2: Sketch of precision electrochemical machining integer impeller

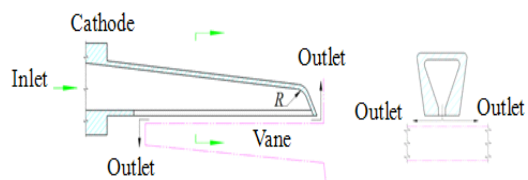

Fig. 3: Sketch of interelectrode gap

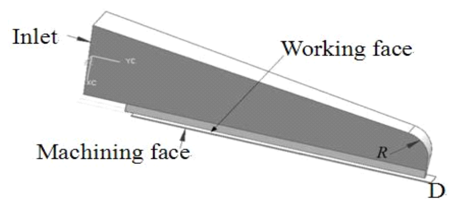

Fig. 4: 3-D model of electrolyte flow flied

Figure 4 shows the 3-D model of electrolyte flow flied during NC precision electrochemical machining integer impeller. The machining area is part of workpiece surface that opposite the working face of cathode. Whether the electrolyte flow field is symmetrical on machining, it will decide the precision and quality of product and the stability of machining process. As a result, the state of electrolyte on machining area is the key problem of simulation analysis. According to hydrodynamics, the electrolyte flow line and flow direction on machining area is shown in Fig. 5. In Fig. 5, electrolyte distributing on machining area is symmetrical except D point, and the D point will be lack of electrolyte for electrochemical machining. In order to augment electrolyte and amend the uniformity of flow field, the value of R shows in Fig. 3 and 4 will be optimized.

CDF SIMULATION METHOD OF 3-D FLOW FIELD MODEL

The electrolyte flow field during ECM is difficult to be accurately controlled due to the complex nature of the involved electrochemical, thermal and hydrodynamic composite action. In order to simplify the CFD simulation analysis under keeping the necessary accuracy, the following assumptions are made:

- The flow in interelectrode gap is assumed as a one phase flow containing only the liquid electrolyte, and the liquid is assumed as a continuum and incompressible perfect fluid. Since the machining area NC-ECM is smaller, the amount of electrolytic products (such as solid, gas, heat) owing to the anodic dissolution and the cathodic reaction are very small.
- ECM process is a balance state that the distance of interelectrode gap is constant.Based on the above assumptions and theory of CFD, the governing equations of electrolyte flow field for numerical simulation includes mass conservation equation and momentum conservation equation.

◦ Mass conservation equation:

$$\frac{\partial P}{\partial t}+\frac{\partial(Pu)}{\partial x}+\frac{\partial(Pv)}{\partial y}+\frac{\partial(Pw)}{\partial z}=0 \qquad (1)$$

where *r* is the density of electrolyte, in the model discussed in this paper *r* =constant; *t* is the time; *u*, *v* and *w* is component velocity of electrolyte velocity vector $\bar{v}$ along x, y and z axis.
Introduce the vector symbol:

$$div(a)=\frac{\partial a_x}{\partial x}+\frac{\partial a_y}{\partial y}+\frac{\partial a_x}{\partial z} \qquad (2)$$

Mass conservation equation in this model could be written as:

$$div(\bar{v})=0 \qquad (3)$$

◦ Momentum conservation equation:

$$\begin{cases}\frac{\partial(pu)}{\partial t}+div(pu\bar{v})=-\frac{\partial p}{\partial x}+\frac{\partial\tau_{xx}}{\partial x}+\frac{\partial\tau_{yx}}{\partial y}+\frac{\partial\tau_{xx}}{\partial z}+F_x\\ \frac{\partial(pv)}{\partial t}+div(pv\bar{v})=-\frac{\partial p}{\partial y}+\frac{\partial\tau_{xy}}{\partial x}+\frac{\partial\tau_{yy}}{\partial y}+\frac{\partial\tau_{xy}}{\partial z}+F_y\\ \frac{\partial(pw)}{\partial t}+div(pw\bar{v})=-\frac{\partial p}{\partial z}+\frac{\partial\tau_{xx}}{\partial x}+\frac{\partial\tau_{yx}}{\partial y}+\frac{\partial\tau_{xx}}{\partial z}+F_x\end{cases} \qquad (4)$$

where *p* is pressure on flow element; τ_{xx}, τ_{xy} and τ_{xz} are component of viscosity stress; F_x, F_y and F_z are volume force, when the gravity force is only one volume force working on flow element, $F_x = 0$, $F_y = 0$. $F_z = -\rho g$. On the assumption that the electrolyte is perfect fluid, the ρ and μ are constant. The momentum conservation equation could be writing as follow:

$$\begin{cases}\frac{\partial(pu)}{\partial t}+\_\,div(pu\bar{v})=div(\mu grad\mu)-\frac{\partial p}{\partial y}+Fu\\ \frac{\partial(pv)}{\partial t}+\_\,div(pv\bar{v})=div(\mu gradv)-\frac{\partial p}{\partial y}+F_v\\ \frac{\partial(pu)}{\partial t}+\_\,div(pw\bar{v})=div(\mu gradw)-\frac{\partial p}{\partial z}+F_w\end{cases} \qquad (5)$$

In order to resolve above equations, a nonlinear *k-e* two equation turbulence model based on Boussinesq assumption need to be introduced. The nonlinear *k-e* two equation turbulence model could be writing as:

$$\begin{cases}\frac{\partial(pk)}{\partial t}+\frac{\partial(pkui)}{\partial xi}=\frac{\partial}{\partial xj}\left[\left(\mu+\frac{\mu_t}{\partial_k}\right)\frac{\partial K}{\partial xj}\right]\\ \qquad +G_k-p\varepsilon\\ \frac{\partial(p\in)}{\partial t}+\frac{\partial(p\in ui)}{\partial xi}=\frac{\partial}{\partial xj}\left[\left(\mu+\frac{\mu_t}{\partial_t}\right)\frac{\partial\in}{\partial xj}\right]\\ \qquad +\frac{C_{1z}\in}{K}G_k-C_{2x}p\frac{\in^2}{K}\end{cases} \qquad (6)$$

where, $\mu=PC\mu\frac{K^2}{\in}$ is turbulent viscosity; G_k is produced by turbulent kinetic energy; C_m, C_{1e}, C_{2e}, s_k and s_e are model constant, according to the results of experimentation and recommendation given by a lot of researcher: C_m= 0.09, C_{1e} = 1.44, C_{2e} = 1.92, s_k = 1.0, s_e = 1.3.

In order to optimize the value of R mentioned in section 2, shown in Fig. 3 and 4, many flow field models with different R and same boundary conditions have been analyzed by numerical simulation based on above CFD governing equation. Figure 6 and 7 shows the results of simulation analysis.

According to Fig. 6 and 7, when R≤20 mm, following the value of R increasing, the pressure grads of flow field near by D point in machining area gradually smoothing, and the electrolyte velocity increasing there. As a result, the electrolyte flow field becoming more uniform and stabile. But when R = 30 mm, compare with others, the electrolyte velocity near by D point in

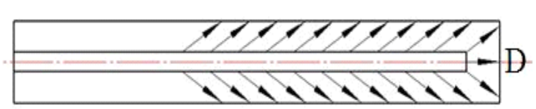

Fig. 5: Sketch electrolyte flow line

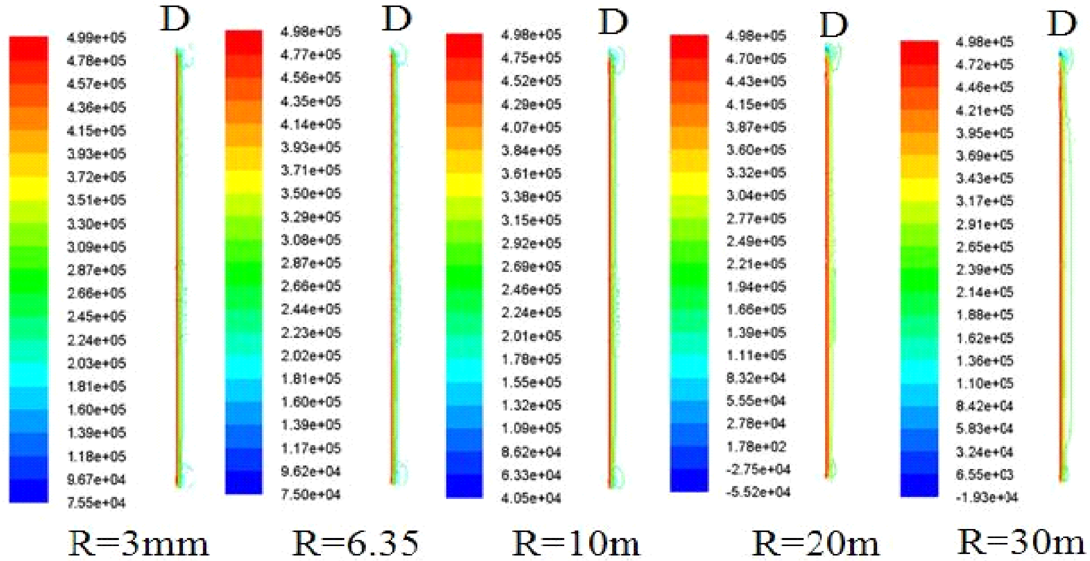

Fig. 6: Electrolyte pressure in machining area

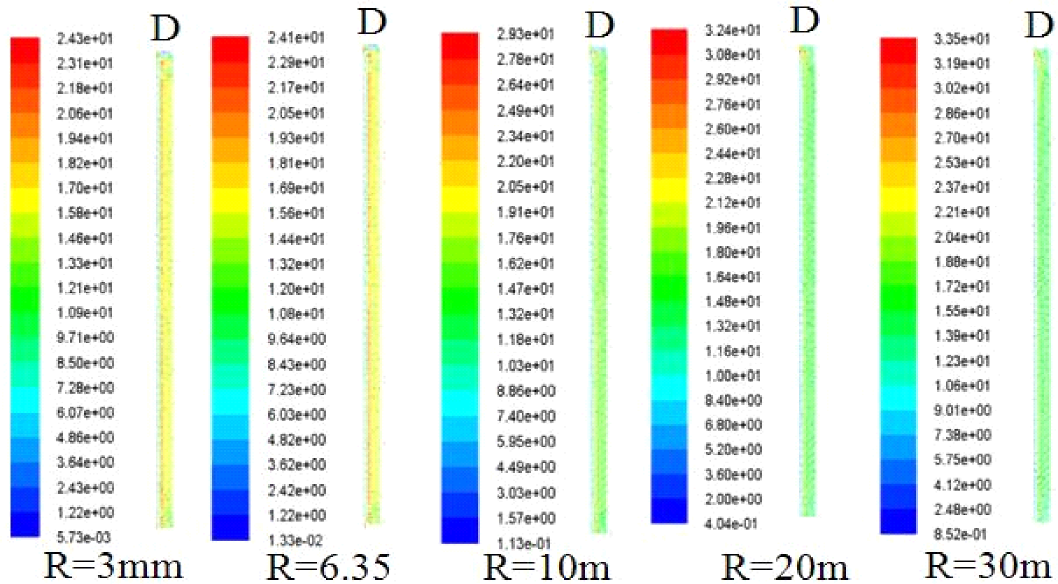

Fig. 7: Electrolyte velocity on machining area

machining area increasing in evidence, and the electrolyte pressure of there becoming low. The uniformity and stability of electrolyte flow field destroyed. The results of numerical simulation indicate that the ideal value of R will larger than 20 mm and smaller than 30 mm. Figure 8 shows that results of simulation analysis when R = 25 mm. From the results we can see that the distribution of pressure grads, velocity and turbulent energy in machining area are symmetrical and steady.

When the structure of cathode has been determined, the electrolyte pressure (p) of inlet of cathode will affect the flow field in interelectrode gap during machining, thus it is an important parameter in ECM. In order to optimize the parameter of electrolyte pressure of inlet , many experiment have been made, Figure 9 shows three results of these experiment. According to Fig. 9, when the initial electrolyte pressure of inlet p = 0.4MPa, the distribution of electrolyte pressure on machining area in workpiece surface is suitable for ECM. According to Fig. 9, when the initial electrolyte pressure of inlet p = 0.4 MPa, the distribution of electrolyte pressure on machining area in workpiece surface is suitable for ECM.

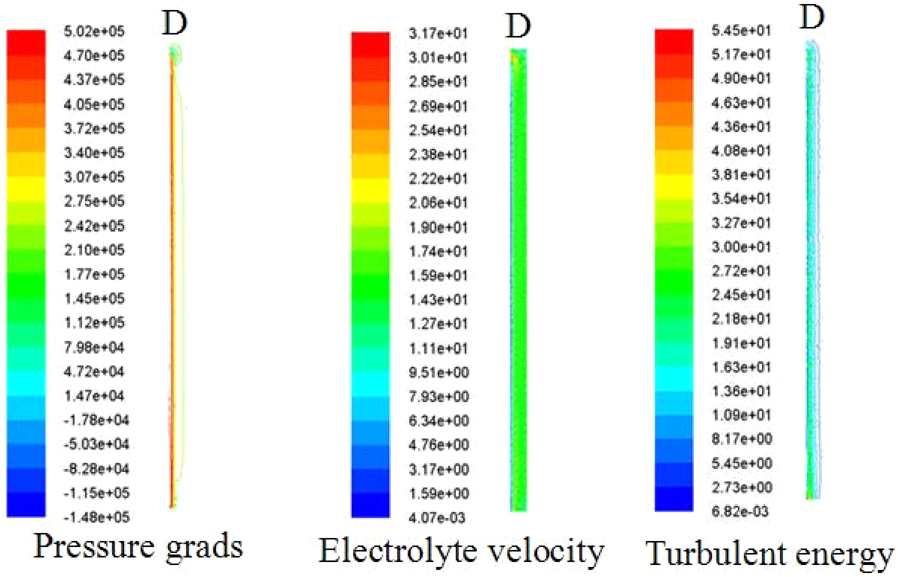

Fig. 8: Results of simulation analysis when R = 25 mm

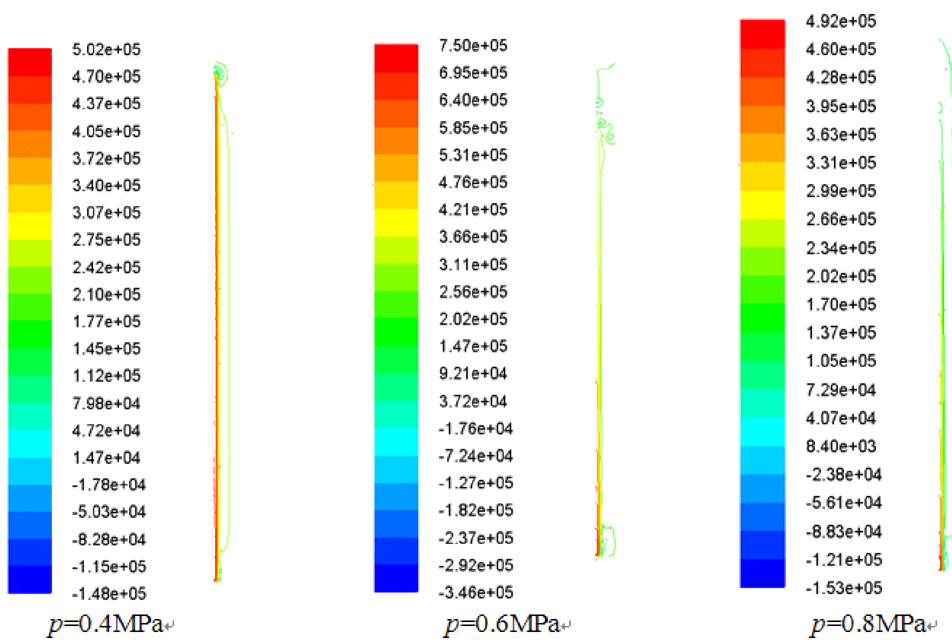

Fig. 9: Results of simulation with different initial electrolyte pressure

EXPERIMENT

In order to verify the proposed method of numerical simulation based on CFD, two cathodes have been made, one R = 6.35 mm, the other R = 25 mm. In experiments, the electrolyte flow field of machining face on workpiece is difficult to observe, on other hand, the direction of electrolyte flow could be observed easy. So, we analysis the direction of electorlyte flow in cathode internal channal based on 3-D numerical model, and compared simulation results with that of experiments. Figure 10 shows that the results of numerical simulation of electrolyte flow field in cathode internal channal based on 3-D model. Figure 11 shows the electrolyte flowing out of

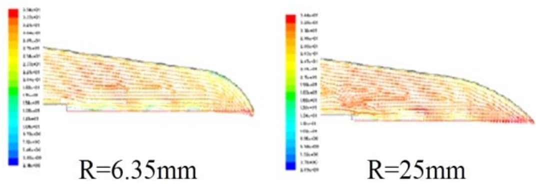

Fig. 10: Results of simulation analysis of flow field in cathode

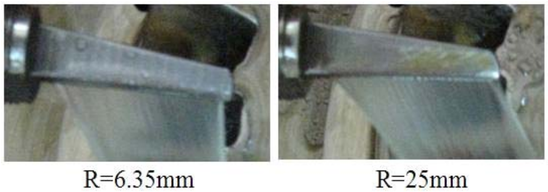

Fig. 11: Experiment of electrolyte flow

Fig. 12: Photo of vanes with trace of flow field

slot in cathode working face. The initial electrolyte pressure of inlet of internal channel in cathode is 0.4 Mpa in simulation and experiment. Figure 10 and 11 shows that the results obtained from the numerical simulation is closer to the experimental.

The test vane was machined using the cathode R = 25 mm, and the initial electrolyte pressure p = 0.4 Mpa, Figure 12 shows the photo of vanes after NC precision electrochemical machining. The trace of electrolyte flow on vane surface during NC-ECM was caused by the flow field in interelectrode gap.

CONCLUSION

A method of applying CFD to aid designing flow field structure of cathode and select parameter of machining in NC precision electrochemical machining integer impeller is proposed. The numerical simulation results of 3-D flow field in interelectrode gap are consistent with the experimental results. Combined with the researchers skills and experiences, the 3-D numerical simulation method described in this paper could is useful for designing the cathode flow structure and selecting parameters for NC-ECM. Results of actual experiment indicated that this method could improve the efficiency of cathode designing and process stability in NC precision electrochemical machining integer impeller.

ACKNOWLEDGMENT

This research was supported by the pre-research project of Chinese National Defense Science and Technology in the Tenth-Five plan and the graduate student innovation plan of Jiangsu province (2003), China.The authors would like to express appreciations to Xu Jiawen and Zhao Jianshe in Nanjing University of Aeronautics and Astronautics, for their valuable comments and other helps in experiments mentioned in this paper.

REFERENCES

Adam, R. and M. Zybura-Skrabalak, 2001. The mathematical modelling of electrochemical machining with flat ended universal electrodes. J. Materials Proces. Technol., 109: 333-338.

Bhattacharyya, S., A. Ghosh and A.K. Mallik, 1997. Cathode shape prediction in electrochemical machining using a simulated cut-and-try procedure. J. Materials Process. Technol., 66: 146-152.

Chang, C.S., L.W. Hourng and G.T. Chung, 1999. Tool design in electrochemical machining considering the effect of thermal-fluid properties. J. Appl. Electrochem., 29: 321-330.

Chang, C.S. and W. Hourng, 2001. Two-dimensional two-phase numerical model for tool design in electrochemical machining. J. Appl. Electrochem., 31: 145-154.

Chunhua, S., D. Zhu and Z. Li, 2006. Application of FEM to tool design for electrochemical machining freeform surface. Finite Elements Analy. Design, 43: 168-172.

Hunt, R., 1990. An embedding method for the numerical solution of the cathode design problem in electrochemical machining. Inter. J. Numer. Meth., Eng., 29: 1177- 1192.

Jerzy, K., F.B. Antoni and D. Piotr, 1998. Computer simulation electrochemical shaping (ECM-CNC) using a universal tool electrode. J. Mater. Proces. Technol., 76: 161-164.

Jerzy, K., M. Chuchro and R. Adam, 2000. The computer aided simulation of electrochemical process with universal spherical electrodes when machining sculptured surfaces. J. Materials Proces. Technol., 107: 283-287.

Pajak, P.T., A.K.M. Desilva and D.K. Harrison, 2006. Precision and efficiency of laser assisted jet electrochemical machining. Precision Engine., 30(3): 288-298.

Peng, W.Y. and Y.S. Liao, 2004. Study of electrochemical discharge machining technology for slicing non-conductive brittle materials. J. Mater. Proces. Technol., 149(1-3): 363-369.

Rajurkar, K.P. and D. Zhu, 1999. Improvement of electrochemical machining accuracy by using orbital electrode movement. Annal. CIRP., 48: 139-142.

Wu, R., X. Jiawen and Z. Jianshe, 2008. Fluid Field Simulation of Electrochemical Machining Cavities Based on Software of CFD. China Mech. Engine., 19(14): 1657-1660.

Wüthrich, R. and V. Fascio, 2005. Machining of non-conducting materials using electrochemical discharge phenomenon-an overview. Inter. J. Machine Tools Manufacture, 45(9): 1095-1108.

Xu, J., Y. Naizhang and T. Yangxin, 2005. The modelling of NC-electrochemical contour evolution machining using a rotary tool-cathode. J. Mater. Proces. Technol., 159: 272-277.

Zou, Y.M. and J.D. Jeffrey, 1995. The cathode design problem in electrochemical machining. Chem. Engine. Sci., 50(17): 2679-2689.