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Simulation of Electrochemical Shaping of Airfoils Using Continuous and Pulse Current

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***Abstract*—Electrochemical machining using continuous and pulse current (ECM, PECM) provides an economical and effective method for machining high strength, heat-resistant materials into complex shapes such as airfoils made of titanium alloys. The dimensional accuracy of ECM/PECM can be improved if a small inter electrode gap is maintained. This paper presents the recent work in the shaping of airfoils by using sequence of ECM and PECM treatments.**

***Index Terms*— accuracy, airfoil, electrochemical machining, pulse current**

I. Introduction

Electrochemical machining (ECM) is based on a controlled anodic electrochemical dissolution process of the workpiece (anode) with the tool (cathode) in an electrolytic cell, during an electrolysis process (Fig. 1.).

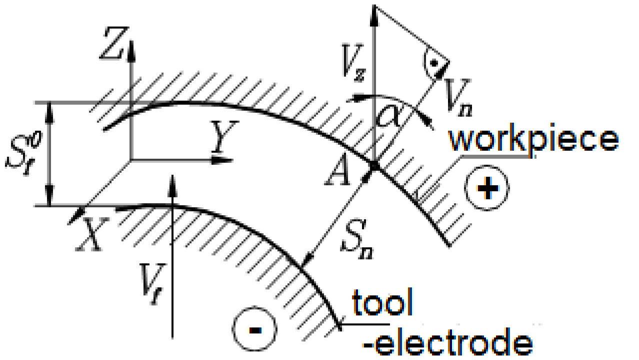

Fig. 1. Schematic diagram of electrochemical machining (ECM)

As electrochemical dissolution proceeds, the tool electrode-cathode can be fed mechanically towards the workpiece - anode in order to maintain the machining action. Under these conditions, the inter-electrode gap width gradually tends to a steady-state value, and a shape, complementary to that of the cathode-tool, is reproduced approximately on the anode-workpiece. The final gap distribution depends on the shape of tool electrode, kinematics of tool electrode, electrical and hydrodynamic parameters in the gap and basic characteristics of anodic dissolution.

Being a non-mechanical metal removal process, ECM is capable of machining any electrically-conductive material with high stock removal rates regardless of their mechanical properties. In particular, removal rate in ECM is independent of the hardness, toughness and other properties of the material being machined. Moreover, surface of work piece machined by any of ECM processes is of high quality and stress free. The use of ECM is most warranted in the manufacture of complex-shaped parts from materials that lend themselves poorly to machining by other, above all mechanical, methods. There is no need to use a tool made of a harder material than the workpiece, and there is practically no tool wear.

Various variants of ECM like: electrochemical sinking, ECM with numerically controlled tool electrode movement, ECM with orbiting tool electrode, pulse ECM, electrochemical smoothing, electrochemical deburring are used in industrial practice. Therefore, use of ECM for production of dies, parts of turbine engines, medical implants, parts for electronic and military industries etc is well justified. In particularly ECM is very significant in manufacturing of turbine and compressors airfoils The examples of airfoils machined by ECM- illustrated Fig.2.

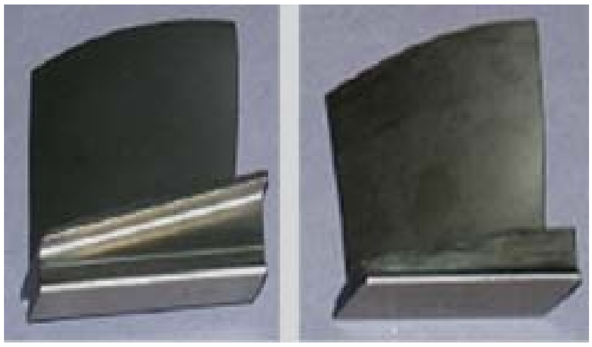

Fig. 2. Examples of airfoils shaped by ECM

Industrial practices in ECM have revealed some problems impeding its further development and wider acceptance by industrial users. Among them, prediction and control of the local inter electrode gap distribution (and hence, the control of dimensional accuracy), along with the design of tool electrodes for complex work piece shapes and optimization of process, are the major problems encountered by ECM users.

Basic investigations and practice have indicated that electrochemical machining using pulsed current (PECM) has a great potential to offer a systematic solution to the above problems.

II. Accuracy Problem in ECM

Improvement in precision prediction of distribution gap size i.e. more exact determination of final shape of workpiece or tool electrode profile for requirement contour workpiece is basic problem due to machining accuracy. One way of solution this problem is reducing changes in the gap size along surfaces by using technical means

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Let us consider changes of gap size in steady state contoured ECM by using approximation for the gap size, widely used in practice i.e. expressed by equation:

$$S_n = \frac{S_f}{\cos\alpha} \qquad (1)$$

where: α is angle between a normal direction to anode and the direction of feed rate of the tool-electrode V_f (Fig.1), and S_f is equilibrium gap size. The equilibrium gap size is equal:

$$S_f = \kappa \cdot K_V \frac{U-E}{V_f} \qquad (2)$$

where K_V is the coefficient electrochemical machinability, which is defined as the volume of material dissolved per unit electrical charge, U is the working voltage and E is the total overpotential.

The difference in the gap size can be estimated from variation in the equilibrium gap S_f along flow electrolyte direction. The change in the equilibrium gap at angle α (Fig.1) is approximately given by

$$\Delta S_n = \left(\Delta\kappa/\kappa + \Delta K_V / K_V - \Delta E / E\right)\cdot \frac{S_f}{\cos\alpha} \qquad (3)$$

where $\Delta\kappa$ is the increment of the electrical conductivity κ, ΔK_V is the increment of K_V and ΔE-increment of E.

Equation (3) may be used for approximate analysis of ECM accuracy and tool-electrode design.

These approximate analyses led to the conclusion, that machining inaccuracy is proportional to the gap size. The shape error is depending on deviation of properties medium in the gap and physical conditions, such as electrical conductivity, temperature T, void fraction β, current efficiency (electrochemical machinability), flow velocity w, pressure p, etc.

Therefore, for improvement of shape accuracy and simplification of tool design, the gap size during ECM should be smaller as possible. Additionally, more stables the gap state is needed by reduce non-uniformity of electrical conductivity and other physical conditions, which are significant for dissolution process.

These requirements for ECM performance, with continuous working voltage is very limited. The minimum practical tool gap size, which may be employed, however is constrained by the onset of unwanted electrical discharges. These short electrical circuits reduce the surface quality of the workpiece, and led to electro-erosive wear of the tool-electrode, and usually machining cannot progress because of them. Investigations of electrical discharges in an electrolyte reveal that the probability of electrical breakdown the gap is a function of the evolution of gaseous-vapor layers and passivation of the work surface. Intense heating, hydrogen generation sometimes choking phenomena and cavitation within the gap can lead to evaporation and subsequent gas evolution, and it is this gas which is believed to cause the onset of electrical discharge. The issue of heating of electrolyte is primary importance for the determination of limit condition of ECM process.

All these constrains of continuous ECM can be eliminated and the requirements with view of points of machining accuracy can be achieved by application of pulse working voltage [1] – [10].

In the pulse electrochemical machining (PECM) process, a pulse generator is used to supply the working voltage pulses across the two electrodes, typically in the form of pulse strings consisting of single pulses or grouped pulses(Figure3). The anodic electrochemical dissolution occurs during the short pulse on-times t_p, each ranging from 0.1 ms to 5 ms. Dissolution products (sludge, gas bubbles and heat) are flushed away from the inter-electrode gap by the flowing electrolyte during the pulse off-times between two pulses or two groups of pulses. To intensify the electrolyte flushing, the tool is retracted from the workpiece to enlarge the gap during the pulse off-times. The gap checking and tool repositioning can also be conducted during these pulse pauses to establish a given gap size before the arrival of the next pulse, leading to a significant reduction in the indeterminacy of the gap and, hence, of the shaping accuracy.

In the result, the continuous ECM is replaced with discrete process, which makes possible to reduce the gap size below 0.1 [mm], and to set the gap size intermittently by controlling (monitoring) the position of the machining surface during the pause between pulses.

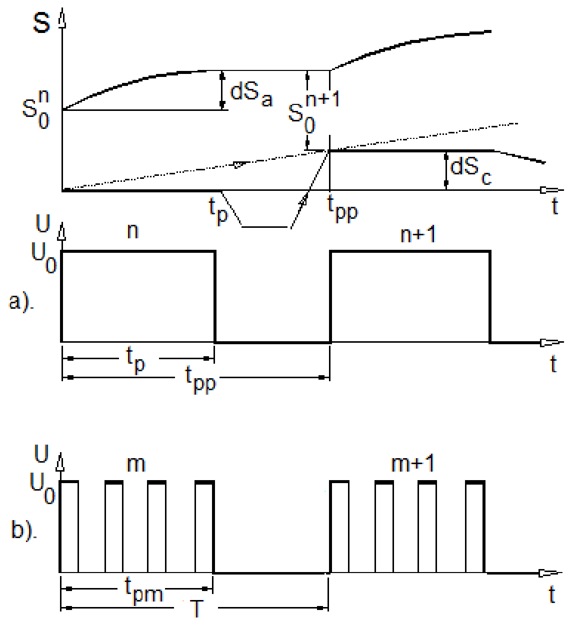

Fig.3. A scheme of PECM with (a) single voltage pulses and (b) pockets/grouped pulses.

Practice and investigations shows that introducing of PECM allows:

- Diminish the inter-electrode below 0.1 [mm], what is one of the fundamental condition of increasing ECM accuracy,
- Reduce the inaccuracy of the machined profile caused by internal disturbance of physical and chemical properties of electrolyte (more exact: medium in the gap) in inter-electrode gap,
- Simplify of tool design since the much more uniformity distribution of the gap size,
- Eliminate the macro - defects on the machined surface connected with the hydrodynamics flow disturbance,
- Monitoring and control the gap sizes on line i.e. during machining cycle.

Material processing by a pulse electrochemical machining (PECM) is a complicated process with specific

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characteristic features. Systematization and substantiation of anodic dissolution in the process of pulse electrochemical machining and the identification of interactions between different phenomena during this process are important for the achievement of maximum accuracy, machining quality and productivity at various technological parameters.

III. Mathematical Modeling of the PECM process

The relations between main factors occurring during Pulse ECM are shown schematically in (Fig. 4),

All physical fields in the gap are non-stationary during whole time of machining. Since properties of electrolyte such as electrical conductivity κ are depending on temperature ,T, and gas phase concentration ,β , which distributions depend on flow velocity ,w, and pressure fields ,p, as well as on current density i, PECM processes have to be described by set of mass, heat and electric charge transfer equations.

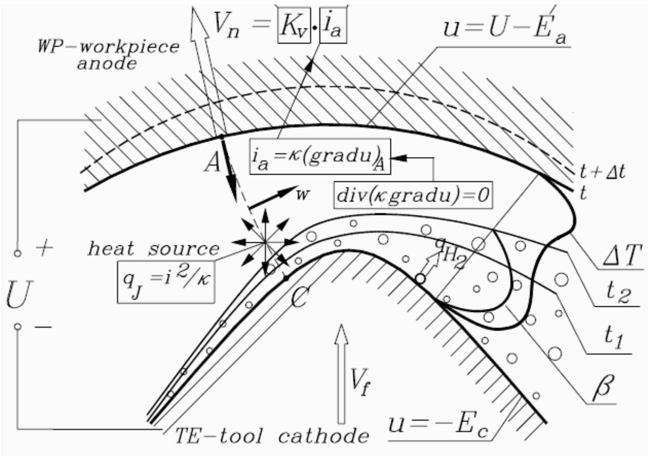

Fig. 4: Schematic diagram of the physical state in the gap :i - current density, U - pulse voltage, u - electrical potential, E_a,E_c - overpotential on anode and cathode.

Most models so far assume that the gap is filled with a continuous pseudo-homogeneous two-phase medium: fluid-electrolyte and gas bubbles. A *homogeneous model* of PECM process has been reported and analyzed by many authors [1] – [10].

The hydrogen generated on the cathode surface appears as a layer of bubbles mixed in the electrolyte, and this layer thickness is increasing across gap size in time and along flow path (Fig.4). Since in some cases of PECM it is necessary to take the *multi-layers models* of PECM process into consideration for the mathematical description [1], [4], [7].

Mathematical approximation of the pulse electrochemical processes, with using homogeneous or multi-layers models, depends on the Strouhal number: $St=L/wt_p$, where L is characteristic length of the machining surface along flow path and t_p pulse on-time. When St << 1, the mathematical description is almost the same as that for the continuous ECM. In this case, the convective terms of transport equations of PECM process plays the main role and time be regarded as a parameter. At number St >> 1, what occurs when machining is performed at low electrolyte flow or with short pulse on – time, the pulse process differs considerably from the continuous one. The proceeding processes are visible nonstationary. In their mathematical description the local derivative play the greatest role and in number of cases the mass and energy transfer by convection may altogether be neglected. Also, in the modeling process, the electrochemical dissolution and diffusion processes should be accounted for by introducing the anodic dissolution efficiency η or electrochemical machinability K_V, and the total overpotential E. In a PECM conditions, both are variables of time. Since analytical models of characteristics for η or K_V and E are not available, experimental results should be used with theoretical models.

The main objectives of mathematical modeling of the PECM are:

- determination the thickness of anodic metal removal ΔS, and the average metal removal rate V_a, during a single pulse or a grouped pulses,
- determination the physical conditions in the gap during pulse current, such as distribution of temperature increment θ, void fraction β, and pressure p,
- determination the quasi-steady sate distribution of the gap size S along the electrode surface, as base of tool-electrode design and the accuracy analysis.

The following conditions are assumed:

- Temperature of the tool electrode and workpiece are constant,
- Electrochemical and diffusion processes are accounted for by introducing the parameters η and E, where $E = Ea - Ec$ and Ea , Ec are the overpotentials of the anode and the cathode, respectively.
- Ohm's law is applicable in the inter-electrode gap,
- The gas generation is negligible due to the application of short pulse on-times or hydrogen free electrolytes.

Under the above assumption, the Joule heating is the dominant factor affecting electrolyte properties in the gap.

To formulate the mathematical model, a general 2-D case which describes change in shape of the surface of the workpiece can be examined by using coordinate system attached to the tool-electrode *(x, y)*, and, which is movable during machining (Fig. 5). To simplify the calculations we introduce in this plane a curvilinear coordinate system (ξ, ζ), connected with the tool-electrode. In this coordinates system, ξ lies on the given tool-electrode and is measured from the inlet of the electrolyte. Let axis ζ overlap its normal $\vec{n}_C$ (Fig. 5.).

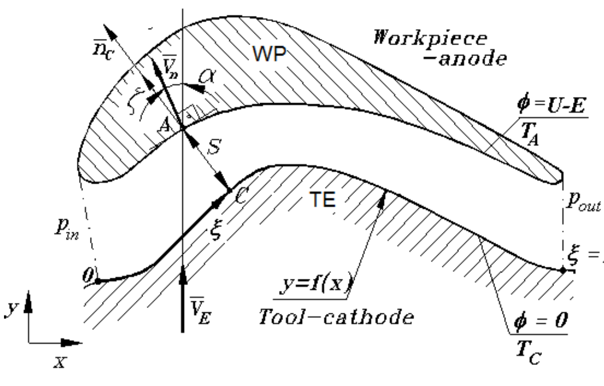

Fig. 5. Schematic the system coordinates and boundary conditions

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The velocity of anodic dissolution V_n during pulse on-time can be obtained from the Faraday's law:

$$V_n = K_v i \tag{4}$$

The current density, i, can be expressed by the Ohm's law:

$$i = \kappa_0 \frac{U - E}{\int_0^S \frac{d\varsigma}{1 + \alpha_T \theta}} \tag{5}$$

where: $\theta = T - T_0$ -the temperature increment, T_0 - initial temperature of the electrolyte, α_T–temperature coefficient of the electrolyte conductivity at T_0, κ_0 is the electrolyte conductivity at T_0.

Too determine the change of the increment temperature θ, caused by Joule heating, an energy balance equation can be written as:

$$\frac{\partial(\rho_e C_p S\theta)}{\partial t} + \frac{\partial(\rho_e C_p wS\theta)}{\partial \xi} = \lambda \frac{\partial^2 \theta}{\partial \varsigma^2} + \frac{i^2}{\kappa} \tag{6}$$

where: ρ_e, C_p and λ are electrolyte density, heat capacity and thermal conductivity respectively.

The convection term in this equation can be neglected for PECM with a short pulse on-time, t_p, and the Strouhal Number $St = L/w \cdot t_p >> 1$. For PECM conditions of electrolyte flow $w < 5$ m/s, pulse on-time $t_p < 10^{-4}$ s, and gap length $L < 0.1$ m, the Strouhal Number will be larger than 250. Neglecting the convection term also implies that, in this particular case, local S, and θ depends only on time.

The boundary conditions are as follows: $T(\xi=0) = To$, $T(\xi, 0) = T_A$, $T(\xi, S) = T_C$, where: T_A and T_C are temperatures of the anode and cathode, respectively. As mentioned above, the mathematical modeling of PECM process also depends on the relation between pulse off – time t_o, flow velocity w and characteristic length L i.e. depend on the Strouhal number for flushing period $St_o = \frac{L}{w \cdot t_o}$. If the time interval between the pulses $t_o = t_{pp} - t_p$ is long enough to ensure a complete renewal of the electrolyte in the gap i.e. when $St_o < 1$ or $t_o > L/w$, it is reasonable to assume that the analysis of the process for a single pulse is valid over a series of pulses. However, if small pulse interval is used, in mathematical modeling additional description is required to track changes in the initial conditions from pulse to pulse so as to apply the models derived under single pulse conditions.

In the PECM process and in the curvilinear coordinate system (ξ, ζ), an evolution of the workpiece shape is described by changes of the distribution of the gap size $S(\xi, t)$ during a single pulse and a pockets pulses:

$$\frac{dS}{dt} = K_V \cdot i - V_E \cos\alpha \tag{7}$$

$$(m-1) \cdot T_{pp} + (n-1) \cdot t_{pp} \le t \le (m-1) \cdot T_{pp} + (n-1) \cdot t_{pp} + +t_p$$

with initial condition for each the working pulse

$$S[t = (m-1) \cdot T_{pp} + (n-1) \cdot t_{pp}] = S^f_{m-1,n}(\xi) - \Delta S^p_C \cdot \cos\alpha(\xi)$$

where ΔS^p_C is the displacement of tool-electrode during a single pulse on – time, and $S^f_{m-1,n}(\xi, t_{m-1,n})$ is a distribution of the gap size at the end of previous (m – 1) pocket pulses .

For estimation purpose, PECM conditions of one-dimensional models can be used, but for more accuracy, PECM parameters of application of two-dimensional models are needed.

An effective method for the solution at $St_0 < 1$, i.e. with full renovation of the electrolyte during pulse off – time, can be made by extending the solution for a single pulse, to a series of pulses and along tool-electrode surface i.e. with considering a differences in the gap sizes along the coordinate ξ.

Another important characteristic of the PECM process is the relation between minimum gap sizes and machining parameters. With the other working conditions being the same, the smaller the gap size, the greater the increase in the electrolyte temperature. If electrolyte boiling is considered as the limit for maintaining a stable machining process, then the expression of the gap size, denoted as S^* can be obtained from simulation with the following conditions:

$$t = t_p^*, \quad \theta = \theta_b$$

where: $\theta_b = T_{boil} - T_0$, and T_{boil} is the boiling temperature of the electrolyte under the gap conditions.

The developed mathematical model of PECM process have been used in developed software for computer simulation of electrochemical shaping.

IV. Manufacturing airfoils with using the sequences of ECM and PECM processes

Disadvantages of PECM is decreasing average feed rate in comparison to continuous ECM. Therefore, application of PECM for removing all allowance usual consuming large time.

For solve this problem can be used the sequence of ECM and PECM processes performed on one machine tool. After ECM stage of shaping, when basic amount of material is removed (approx. 80%) and rough shape with accuracy about 0.1-0.3 mm is obtained , the PECM stage is applied for machining final shape with high accuracy. Main an advantage of this method is very significant reduction of machining time, because material removal rate in ECM stage is more than 5-10 times larger than in PECM.

The sequence ECM-PECM has been used in machining of airfoils as shown in Figure 6.

During the stage of ECM, the frontal gap is reached of the stationary gap S_f , which is initial frontal gap for PECM process.

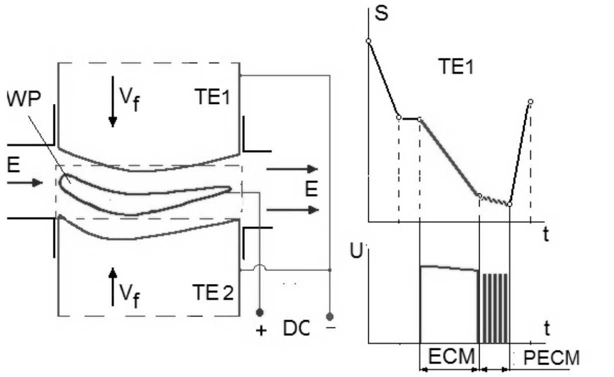

Fig.6. Principal scheme of the shaping of both side of airfoil with using the sequence of ECM and PECM treatments : TE(1,2)-tool electrodes, WP-workpiece, E - electrolyte, DC - power supply of continuous and pulse current.

In the final moment of PECM, the frontal gap size is equal of AC(p) (Fig.7.).

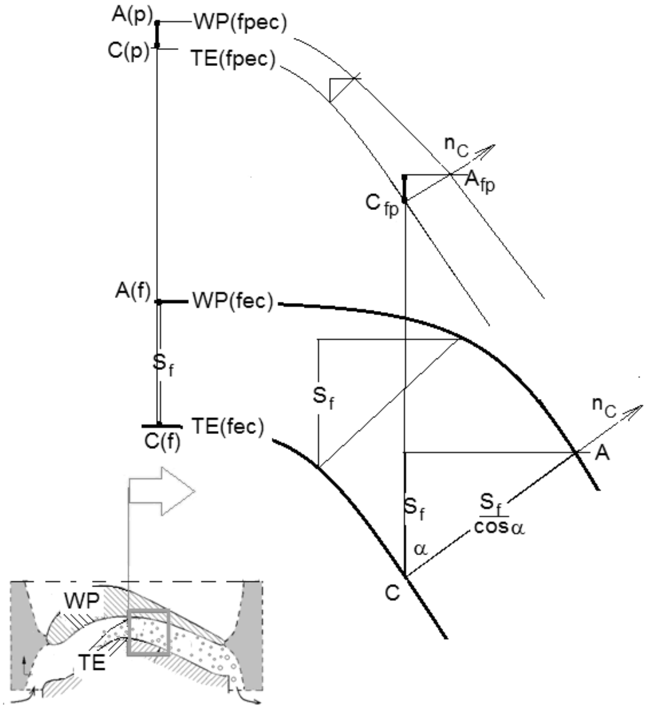

Fig.7. Scheme of the position of the electrodes: TE(fec) and WP(fec): - the positions of the tool electrode and machined profile respectively, in the final moment of ECM stage and the initial moment of PECM; TE(fpec), WP(fpec) – the positions of TE and WP in the final moment of PECM.

For selection of parameters of continuous ECM, the simulation software presented on the WCESC'2011, can be used [11]. The optimal conditions of shaping from the point of view of accuracy and productivity are determined by computer simulation of sequence of both processes (ECM and PECM).

Fig. 8 to Fig. 10 show of the selected results of computer simulation of airfoil shaping at following conditions: material of workpiece, γTiAl; electrolyte 15% NaCl, working voltage, U=15 V; pulse on time, t_p = 2 ms; pulse off time t_{pp} = 5.0 ms; displacement of tool electrode after each pocket (Fig.3) dS_C = 0.005 mm; number of pulses in the pocket N = 115; number of pockets M = 150.

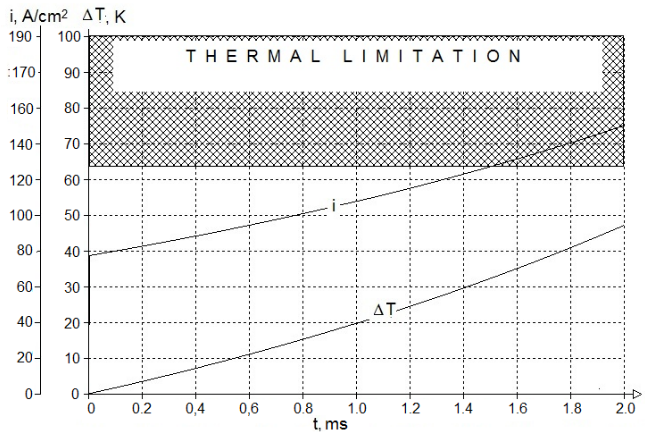

Fig.8. The current density and the electrolyte temperature changes during pulse on – time in last pulse (n=115, m=150)

The changes of current densities and increments temperature during rectangle voltage pulse is shown in 8. During all PECM treatment thermal conditions in the gap has been below limitation.

The evolution in time of the local gap size along airfoil profile i.e. at different angle α, has been determined using the computer simulation,.

Example of changes gap size in time is shown in Figure 8. After a some number of pockets pulses, the gap size practically stabilizes on a quasi-steady state value S_n.

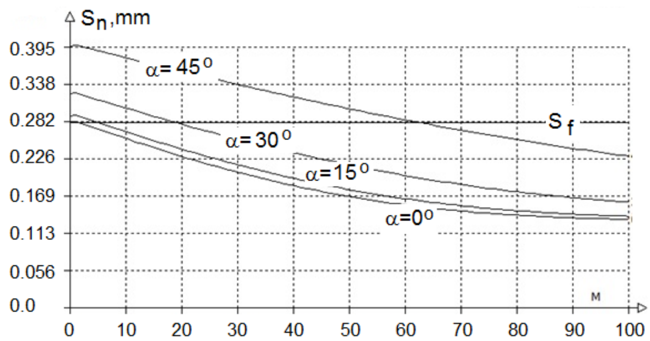

Fig.9. Changes in the local gap size at different angle during serial pulse pocket M

The shape error of airfoil is depend on deviation of gap size along profile, which can be calculated as following: $\Delta S_n = S_n(\alpha) - S_n(\alpha = 0)$.

The distributions of the value ΔS_n along the airfoil profile in quasi-steady state of PECM and steady ECM are shown in Fig.10.

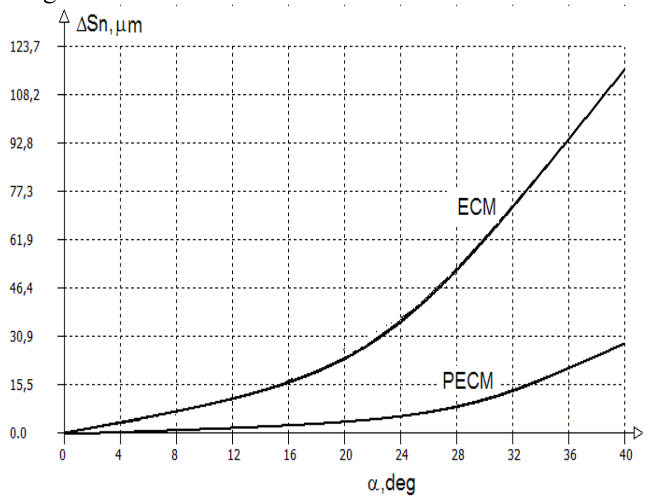

Fig. 10. The distributions of the value of deviation ΔS_n in ECM and PECM processes.

The results of simulation presented in Fig.10, shows that the gap size distribution in the PECM process is more uniform than that in the continuous ECM and the shape errors is more than 4 times smaller. These conclusions has been confirmed by experiments and practice of PECM.

The practice of cooperation with industry shows that the shaping of airfoils using the sequences ECM-PECM processes is an effective way for improve of quality and productivity of ECM technology

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