



NUMERICAL SIMULATION FOR ECM MACHINING OF NONLINEAR SHAPED SURFACES

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Abstract

In this work there has been presented a theoretical analysis of ECM machining curvilinear surfaces. Electrochemical machining with the use of a tool electrode (ECM.S) is one of the basic and most widely used electrochemical technological operations for machining tools and machine parts.

Physical phenomena occurring in the inter electrode gap have been described with partial differential equation system resulting from the balance of mass, momentum, and energy of the electrolyte flowing in the gap.

The equations formulated in the work describing the curvilinear surface shape evolution and the electrolyte flow (mixture of liquid and gas) in the gap, were simplified and then solved in part analytically, in part numerically.

For complex machining parameters there have been performed calculation illustrated with distribution charts: volume fraction, temperature, gap thickness, mean flow velocity, pressure and current density.

Keywords: computer simulation, electrochemical machining, electrolyte flow

1. Introduction

Electrochemical machining with the use of a tool-electrode is today one of the basic operations of electrochemical machining technology for machine elements and other mechanical devices.

In the constant process the tool-electrode (TE) performs most often a translatory motion towards the machined surface. Electrolyte is supplied to the inter electrode gap with high velocity causing carrying away erosion products from the inter electrode space. These are mainly particles of hydrogen and ions of the digested metal. Thus, in such conditions we obtain multi-phase, in general, three dimensional flow [7].

Hydrodynamic parameters of the flow and the medium properties determine the processes of mass, momentum and energy exchange within the inter electrode gap. Properly matched they prevent from occurrence of cavitation, critical flow and volume fraction [1,6,8,9].

The above mentioned processes have significant influence on the electrochemical machining velocity and application properties of the machined surface [3,4,11].

Modeling of ECM involves: determination of the inter electrode gap thickness changes, the machined surface shape evolution in time, and distribution of physico-chemical conditions in the machining area, such as: static pressure distribution, electrolyte flow velocity, temperature and volume fraction [3,10].

The purpose of this work is a theoretical analysis of ECM of curvilinear surfaces on the example of a forming surface a turbo machine blade (Fig.1).

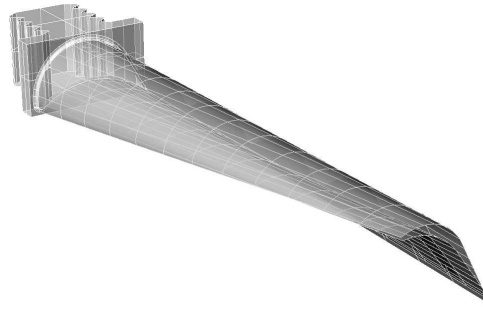


Fig. 1. Turbo machine blade

2. Mathematical model of the ECM process

2.1. Equation describing real shape change of the machined surface

The shape change of the machined surface caused by ECM machining can be described by an equation [3,5]:

$$F_t + k_v J_{A_i} F_i = 0, \quad (1)$$

with an initial condition $F(i, j, 0) = F_0$

here: $J_A = J(i_A, j_A, t)$ - current density distribution on the work piece (WP)-anode,
 k_v - coefficient of electrochemical machinability
 $F_0(i, j) = 0$ - equation describing the shape of the WP-anode in the initial time of machining
 $F(i, j, t) = 0$ - equation describing the actual anode surface.

Current density is described by Ohm's law [3,5]:

$$J_i = -\kappa \left(u \Big|_A \right)_i, \quad (2)$$

here: u - electrical potential,
 κ - electrical conductivity.

The movement velocity of the anode surface points described in an open way by the equation $y = Y_A(i, t)$ is expressed by the formula:

$$v_j = Y_{A,i} = \frac{-v_n}{\cos(n_A, y)}, \quad (3)$$

here:

$$\frac{1}{\cos(n_A, j)} = \sqrt{1 + (Y_{A,i})^2}. \quad (4)$$

The anode velocity v on the basis of Faraday's law is equal :

$$v_{n_i} = k_v J_{A,i}. \quad (5)$$

After introducing dependences (4), (5) and (2) to the equation (3) the equation describing the surface shape change assumes a form:

$$Y_{A,t} = \kappa k_v (u|_A)_i \sqrt{1 + (Y_{A,i})^2} . \quad (6)$$

In the inter electrode gap the electrical field is quasi – stationary, time functions as a parameter, thus, the potential distribution can be described by the following equation:

$$(\kappa u_{,i})_{,i} = 0 \quad (7)$$

with boundary conditions:

- on the tool - cathode $j = f(i) + V_f t ;$
- on the WP - anode $y = F(i, t); u(F) = U - E$
- on the insulator surfaces $u_{,n}|_{GI} = 0$

Assuming linear distribution of the electrical field potential along interelectrode gap (IEG) the current density in the anode, in a locally orthogonal coordinate system (Fig.3) is expressed in the following way [3]:

$$j_A = \kappa_0 \Phi_{TG}^{-1} \frac{U - E}{S} . \quad (8)$$

Function describes changes of the electrolyte conductivity in the inter electrode gap and is determined from the balance of voltage fall along the path h (Fig.2) [3,4]:

$$\Phi_{TG} = \frac{1}{h} \left[\int_0^h \frac{dy}{(1 + \alpha(T - T_0))(1 - \beta)^{3/2}} \right] , \quad (9)$$

where: h - is the smallest distance of a given A point on WP from TE surface.

Introducing the dependency (8) to the equation (6) in an orthogonal kartezyjan system (Fig.1) the searched for velocity of the anode points movement is now described by the dependency:

$$\frac{\partial Y_A}{\partial t} = k_v \kappa_0 \Phi_{TG}^{-1} \frac{U - E}{h} \sqrt{1 + \left(\frac{\partial Y_A}{\partial X} \right)^2 + \left(\frac{\partial Y_A}{\partial Z} \right)^2} . \quad (10)$$

With the initial condition $y = Y(x)$ for $t = 0$

In order to describe the work piece shape evolution on the basis of the equation (10) it is necessary to specify the temperature rise distributions and the volume fraction in the electrolyte.

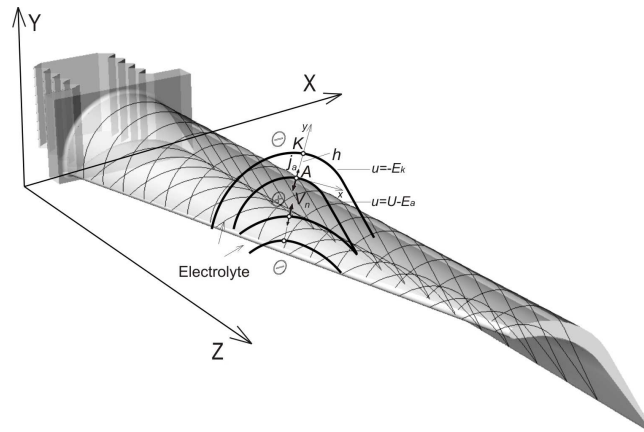


Fig. 2. Scheme of electrochemical machining

2.2. Mixture flow equations in the inter electrode gap

In order to determine the temperature distribution in the inter electrode gap and the volume fraction there have been formulated motion equations resulting from the mass, momentum and energy conservation laws for the considered mixture:

Equations of the flow continuity, respectively, for the electrolyte and hydrogen:

$$\rho_{e,t} + (\rho_e v_i)_{,i} = 0, \quad (11)$$

$$\rho_{h,t} + (\rho_h v_i)_{,i} = J \eta_H k_H h^{-1}, \quad (12)$$

where:

- $\rho_e = (1 - \beta) \rho_e^0$ - electrolyte density,
- $\rho_h = \beta \cdot \rho_h^0$ - hydrogen density,
- v_i - velocity of components,
- k_H - electrochemical equivalent of hydrogen,
- η_H - current efficiency of the hydrogen generation,
- β - volume fraction.

In the equation (11) the erosion products have been neglected assuming that they are negligibly small [2].

Equations of the momentum for the hydrogen and the electrolyte have the form:

$$\rho_e (v_{i,t} + v_j v_{i,j}) = -p_{e,i} + \tau_{ij,j}, \quad (13)$$

$$\tau_{ij} = \mu_e (v_{i,j} + v_{j,i}), \quad (14)$$

$$\rho_H (v_{i,t} + v_j v_{i,j}) = -p_{H,i} + \tau_{ij,j}, \quad (15)$$

$$\tau_{ij} = \mu_H (v_{i,j} + v_{j,i}), \quad (16)$$

here:

- p_e - electrolyte pressure,
- p_H - gas pressure,
- μ_e - dynamic electrolyte viscosity,
- μ_H - dynamic hydrogen viscosity.

The equation of energy for the electrolyte has the form:

$$(\rho_e T_e)_{,i} + (\rho_e T_e v_i)_{,i} = a T_{,ii} + \frac{Q}{c_p}, \quad (17)$$

where:

- T_e - electrolyte temperature,
- $a = \frac{\lambda}{\rho c_p}$ - thermal diffusivity,
- $Q = \frac{j^2}{\kappa}$ - Joule's heat, $j = \frac{\kappa \cdot U_c}{h}$,
- U_c - potential difference.

In order to solve the equation system (11)÷(17) the following simplifying assumptions have been introduced :

- the electrolyte flow is stationary, two-dimensional and laminar
- pressure $p_e = p_H = p$,
- volume fraction $\beta = \beta(x)$
- gap thickness is small in comparison with the inter electrode gap length ($h \ll L$).

Adding the sides of motion equations of both phases, neglecting the flow inertia forces and terms containing ρ_H/ρ_e ($\rho_H/\rho_e \ll 1$), the mixture motion equation system (13)÷(17) in a two-dimensional orthogonal coordinate system is now as follows :

$$\frac{\partial}{\partial x}(\rho_e v_x) + \frac{\partial}{\partial y}(\rho_e v_y) = 0, \quad (18)$$

$$\frac{\partial}{\partial x}(\rho_h v_x) + \frac{\partial}{\partial y}(\rho_h v_y) = j\eta_H k_H h^{-1}, \quad (19)$$

$$\frac{\partial^2 v_x}{\partial y^2} = \frac{1}{\mu} \frac{\partial p}{\partial x}, \quad (20)$$

$$\frac{\partial p}{\partial y} = 0, \quad (21)$$

$$v_x \frac{\partial T}{\partial x} + v_y \frac{\partial T}{\partial y} = a \frac{\partial^2 T}{\partial y^2} + \frac{Q}{\rho_e c_p}. \quad (22)$$

Equations (18, 22) should meet the following boundary conditions :

- for velocity
 - $v_x, v_y = 0$ for $y = 0, y = h$
- for pressure
 - $p = p_o$ for $x = x_o$
- for temperature
 - on the walls:
 - $T = T_0$ for $x \geq x_i$ i $y = 0$ i $y = h$
 - on the inlet:
 - $T = T_i$

where:

x_i - the coordinate of IEG inlet,

x_o - the coordinate of IEG outlet,

T_0 - electrode temperature, T_i - temperature on the inlet.

Solving the equation system (18)÷(21) there have been received distributions of velocity, pressure, and volume fraction in the inter electrode gap in the following form:

$$v_x = \frac{6Q_v}{h^3} (y^2 - yh), \quad (23)$$

$$p = p_w - 12\mu_e Q_v (A(x) - Aw), \quad (24)$$

$$A(x) = \int \frac{dx}{h^3}, \quad (25)$$

$$\beta = \frac{\eta_H k_H R_H}{\mu_H} \frac{\kappa_0 \Phi_{TG}^{-1}(U - E) T}{Q_V h p} x, \quad (26)$$

$$\mu_e = \mu_0 (1 + \beta m) e^{-b(\Delta T)}, \quad (27)$$

here: Q_V – volume rate.

The equation (22) describing the temperature distribution in the gap has been numerically solved with the use of finite difference methods and with the use of the above specified formulas.

3. Numerical model of the ECM process

Determination of the machined surface shape evolution (anode) in time is described by equation (10) describing the real shape evolution of the machined surface.

For numerical calculations there have been performed WP and TE digitization for the cases:

- shaping surface in a global system of perpendicular coordinates described in the following way:

$$x_i = x_0 + i \Delta x,$$

where:

$$i = 0, 1, 2, \dots, I,$$

$$\Delta x = \frac{L}{i},$$

L – WP length towards x axis,

- turbo machine blade through approximation of the surface by curves. In this way a set of TE_k , WP_k curve pairs was received which later were described with assigned accuracy in a global coordinate system by points (Fig. 3),

$$x_i = \sum_{i=1}^i \Delta x_i, \quad (28)$$

where: $i = 0, 1, 2 \dots I$.

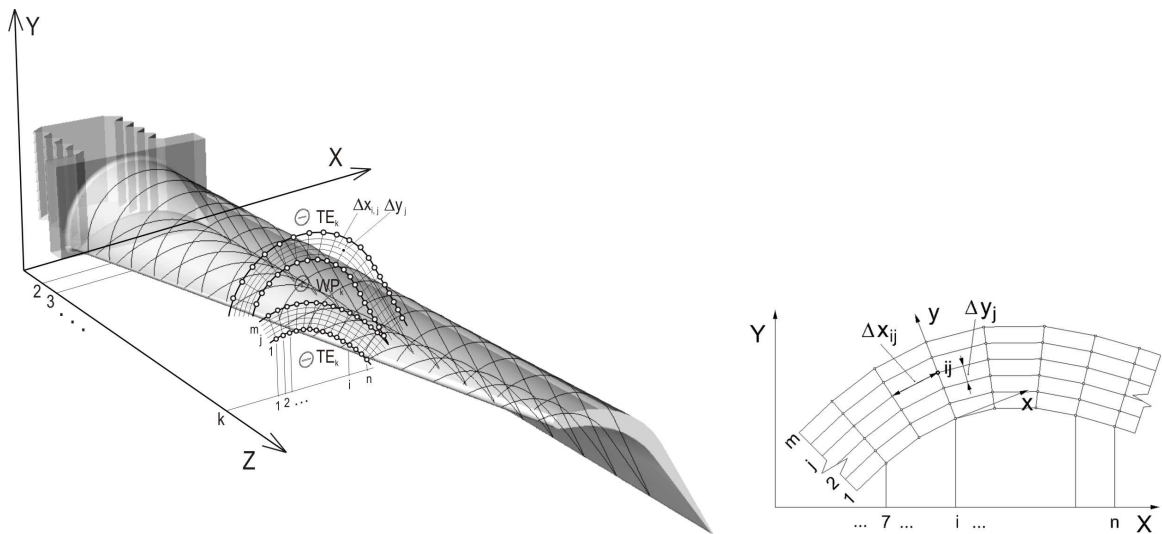


Fig. 3. Digitization IEG

After digitization of the TE and WP surfaces the demanded solution of the equation system describing the mathematical model of the turbo machine blade shape is presented by the computer simulation algorithm of the ECM process (Fig. 4)

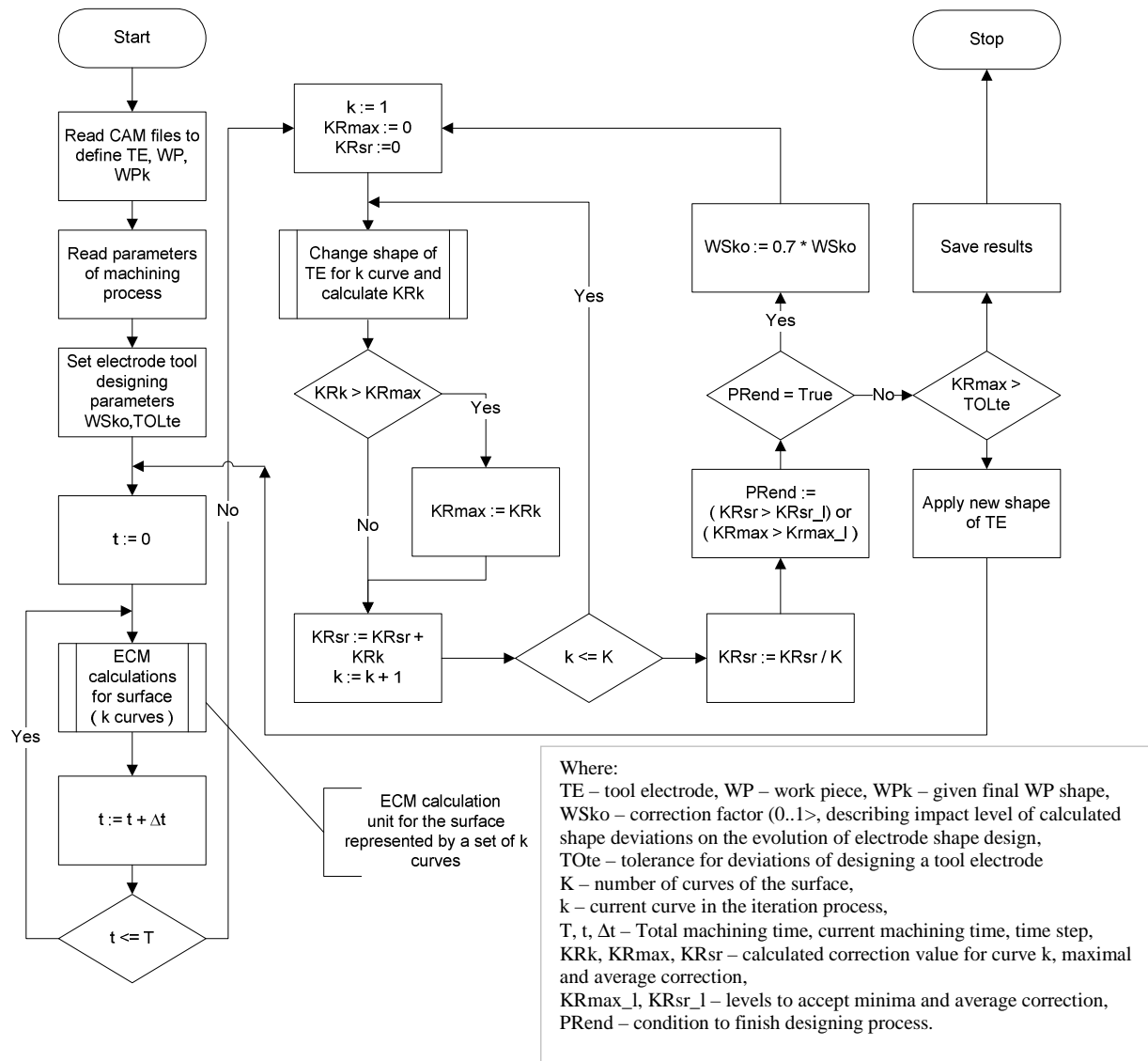


Fig.4. Numerical algorithm simulation of ECM with the ER shape designing procedure

4. Result study

In the calculations it was accepted that the inter electrode gap would be supplied with a constant value of the electrolyte flow volume and the electrolyte would be passivating. calculations were performed until obtaining a stationary state.

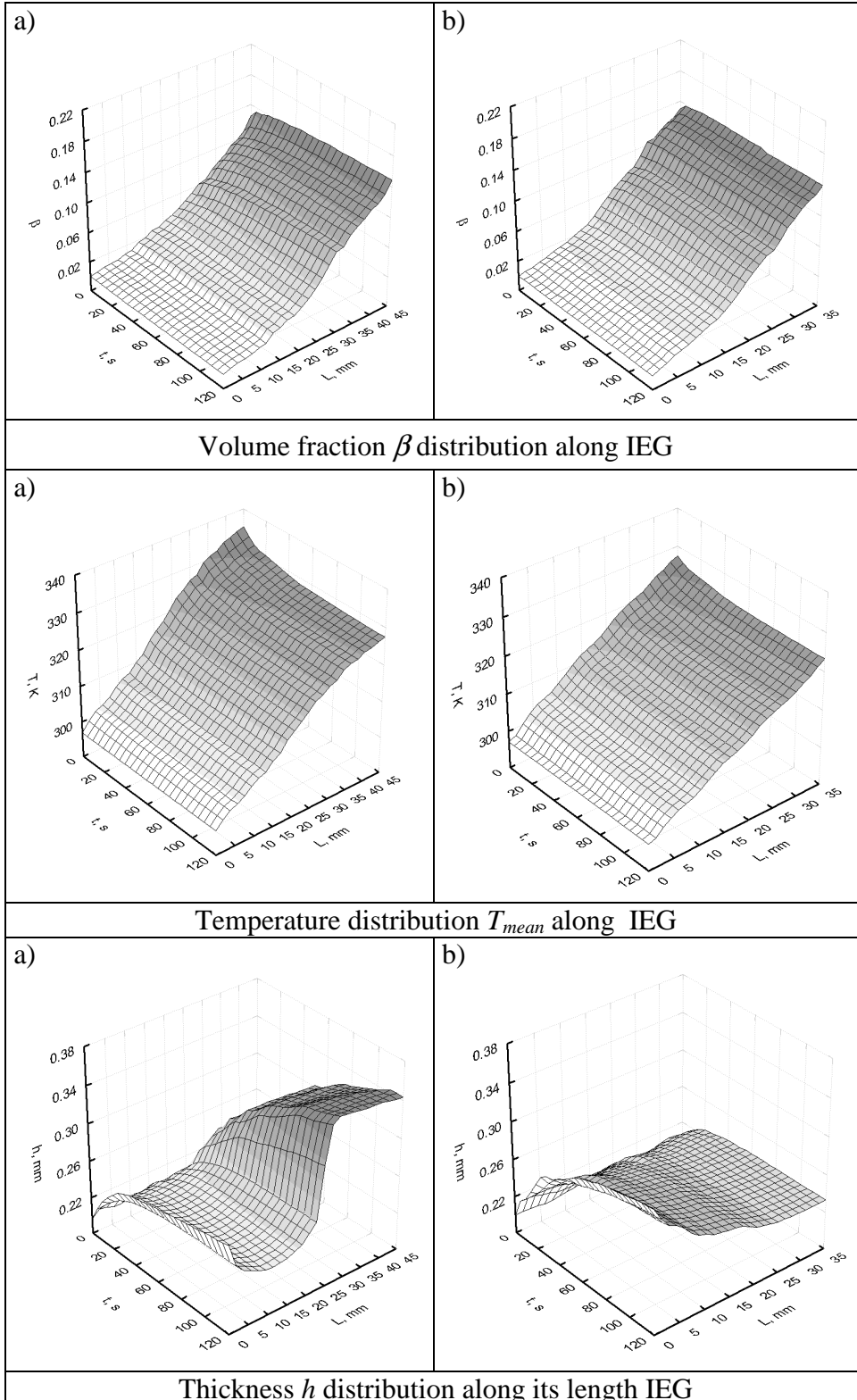
More important machining parameters:

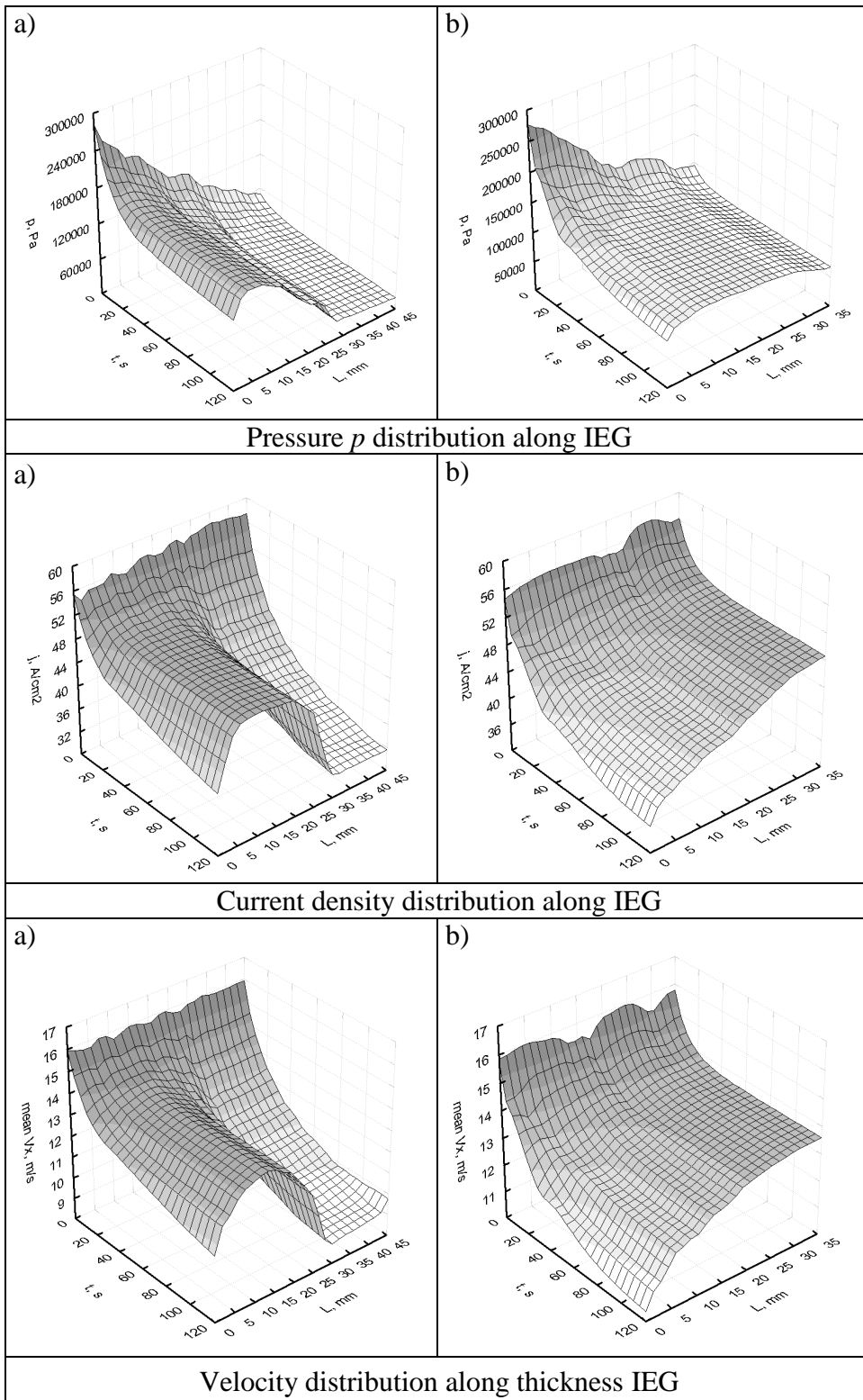
- initial gap - 0.2 mm,
- feed motion velocity TE - 0.0125 mm/s,
- interelectrode voltage - 15 V,

- material WP - WNL,
- material TE - 0H13N9.

Received numerical calculation results have been illustrated in charts of pictures in Tab. 1.

*Tab.1 Distributions of selected physical quantities for:
a) blade upper profile, b) blade lower profile*





In charts of Tab. 1 there have been shown calculation results of the volume fracture, temperature inter electrode gap thickness, pressure, flow density and mean flow velocity distributions for the upper and lower blade profiles of a turbo machine (Fig.1) as well as for the forming surfaces.

From the included charts the following conclusions generally correct for both analyzed curvilinear surfaces can be formulated:

- distribution of filling the inter electrode gap with gas is non-linear,

- the temperature of electrolyte and hydrogen mixture rises gradually along the interelectrode gap in a given machining time,
- local thicknesses of the inter electrode gap for the upper and lower blade profiles are changing. It results from the erosion velocity variability, TE profile angle of inclination to the machining direction and the physical conditions variability in the inter electrode gap
- distributions of pressure, flow density, and mean velocity along the gap result from the gap thickness changes and differ qualitatively for both surfaces of the blade profiles.
- Distributions of physical quantities and the length IEG for both blade profiles differ significantly from each other. Thus mathematical modeling of the ECM process seems to be essential for selection of similar conditions for the blade upper and lower profiles.

It should be emphasized that the solutions have been obtained through analytical and numerical integration of complex partial differential equations.

Further simulation and experimental tests will allow for quantitative verification of the accepted mathematical model.

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