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ECM MACHINING OF CURVILINEAR ROTARY SURFACES

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Abstract

The paper deals with a theoretical analysis of curvilinear rotary surface machining (ECM) by a shaping electrode tool. An equation describing the curvilinear rotary surface shape evolution, and an equation of the electrolyte and gas mixture flow through the gap between curvilinear rotary surfaces, have been formulated. Calculations have been performed for the assumed machining parameters, depicting calculation results along the interelectrode gap. Distributions of: gap thickness, current density, void fracture, temperature, electrolyte flow rate and pressure have been presented in charts.

Keywords*: electrochemical machining, electrolyte flow, mathematical model,*

1. Introduction

Nowadays electrochemical machining by a tool shaping electrode is one of the basic operations of electrochemical technology for machining mechanical devices and tools. ECM machining has been developed as a machining method for alloys of high strength and temperature resistant whose machining used to be extremely complicated using other available methods (Wilson [1]); McGeough [2]).

During a constant process, the tool electrode (TE) usually performs a translation towards the machined surface. Electrolyte is supplied to the interelectrode gap, causing that the dissolution products are carried away from the interelectrode gap (IEG). These are mainly hydrogen atoms and ions of the dissolved metal. In such conditions , a multi-phase and three- dimensional flow [3] is obtained.

Hydrodynamic parameters of the flow and the medium properties determine the processes of mass, momentum and energy exchange in the interelectrode gap. Properly matched, they prevent from formation of cavitation zones, a critical flow, circulation, excessive rise of the electrolyte temperature and void fracture [4].

The above mentioned processes have a significant influence on the electrochemical dissolution velocity and applicability of the machined surface [5].

ECM modeling involves: determination of the interelectrode gap thickness, the machined surface shape evolution in time, and distributions of physical-chemical conditions within the machining area, such as : distributions of pressure, electrolyte flow rate, temperature and void fracture.

Many authors have dealt with the mathematical description of ECM machining, including:

Tipon [8], Fitzgerald, McGeough and Marsh[9], Alkire[10], Davydov, Kozak[11], Sautebin[12], Jain and Pandey[13], Prentice, Tobias,[14], Białecki[15], Hume [16], Zouh [17], Prentice and Tobias [18] and Dukovic [19] and others.

This paper is a theoretical analysis of ECM machining of curvilinear, rotary surfaces.

2. Mathematical model of ECM process

Figure 1 shows the area of electrolyte flow inside the interelectrode gap (IEG), between curvilinear, axially symmetrical surfaces.

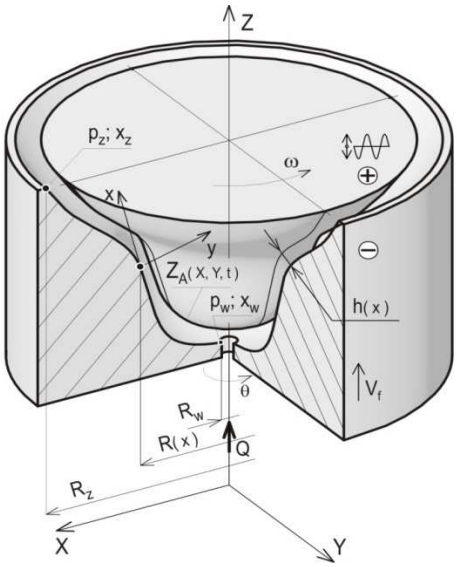

Fig.1. Area flow of electrolyte in interelectrode gap IEG

A general differential equation describing shape evolution of the surface machined by anode dissolution according to ECM dissolution theory, has the form [4,5,6,7]:

$$\frac{\partial F}{\partial t} + k_v \vec{j}_A \, grad F = 0 \tag{1}$$

with initial condition $F(X, Y, 0) = F_0$

where:

$\vec{j}_A = \vec{j}(X_A, Y_A, t)$ - distribution of current density on the machined surface,

k_v - coefficient of electrochemical machinability

$F_0(A,0) = 0$ - an equation describing the initial workpiece (WP),

$F(A, t) = 0$ - an equation describing the anode surface in time t.

Current density results from Ohm's law [4,5,6,7]:

$$\vec{j} = -\kappa \, grad \, u \big|_A \tag{2}$$

where: u - potential of the electrical field between the electrodes,

κ - conductivity.

In rectangular axis X,Y,Z connected with the immovable anode, the anode surface equation has the form:

$$Z = Z_a(x, y, t) \tag{3}$$

Introducing equation(3) into dependence (1), one obtains:

$$\frac{\partial Z_A}{\partial t} = k_V j_A \sqrt{1 + \left(\frac{\partial Z_A}{\partial X}\right)^2 + \left(\frac{\partial Z_A}{\partial Y}\right)^2} \tag{4}$$

where: k_v - coefficient of electrochemical machinability

for $t=0$ $Z_A=Z_o(X,Y)$.

Assuming linear distribution of the electrical field potential along IEG the current density in the anode, in a locally orthogonal coordinate system x,y (Fig.1) is expressed in the following way [6,7,20,21].

$$j_A = \kappa_0 \Phi_{TG}^{-1} \frac{U - E}{h} \tag{5}$$

Function Φ_{TG} describes the influence of conductivity changes within the interelectrode gap (IEG) and is determined in the following way:

$$\Phi_{TG} = \frac{1}{h}\left[\int_0^h \frac{dy}{(1+\alpha(T-T_0))(1-\beta)^{3/2}}\right] \tag{6}$$

In order to close equation system (4),(5) and (6) it is necessary to determine temperature rises $\Delta T=T-To$ and the distribution of void fracture ß. This requires definition of pressure, speed and temperature distributions within the curvilinear interelectrode gap.

Mathematical modeling of the electrolyte flow through he interelectrode gap has been performed in a curvilinear, locally orthogonal coordinate system connected with immobile surface [4].

Having accepted for consideration a model of two phase, anti-slide flow, the mixture movement equations resulting from laws of mass, momentum and energy preservation in curvilinear locally rectangular axis, are in the form [20]:

$$\frac{1}{R}\frac{\partial(\rho_e R v_x)}{\partial x} + \frac{\partial(\rho_e v_y)}{\partial y} = 0 \tag{7}$$

$$\frac{1}{R}\frac{\partial(\rho_H R v_x)}{\partial x} + \frac{\partial(\rho_H v_y)}{\partial y} = j\eta_H k_H h^{-1} \tag{8}$$

$$-\rho_e v_\theta^2 \frac{R'}{R} = -\frac{\partial p_e}{\partial x} + \mu_e \frac{\partial^2 v_x}{\partial y^2} \tag{9}$$

$$\frac{\partial^2 v_\theta}{\partial y^2} = 0 \tag{10}$$

$$0 = -\frac{\partial p_e}{\partial y} \tag{11}$$

here: v_x, v_θ, v_y - components of velocity vector,

p_e – electrolyte pressure,

$\rho_e=\rho_{eo}(1-\beta)$ – electrolyte density,

$\rho_H=\rho_{Ho}\beta$ - hydrogen electrolyte,

μ_e - dynamic coefficient of electrolyte viscosity,

μ_H - dynamic coefficient of hydrogen viscosity,

β - void fraction,

j, η_H, k_H - are, respectively, current density, current efficiency of hydrogen emission, hydrogen electrochemical equivalent,

R - tool electrode surface radius.

Energy equation for the considered flow, taking into consideration Joul's heat, emitted during the current flow, forced heat convection caused by the electrolyte flow, heat exchange by electrodes and negligence of the dispersed energy, has now the form:

$$v_x \frac{\partial T}{\partial x} + v_y \frac{\partial T}{\partial y} = \frac{1}{R}\frac{\partial}{\partial x}\left(a R \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(a \frac{\partial T}{\partial y}\right) + \frac{j^2}{\rho_e c_p \kappa} \tag{12}$$

here: a - coefficient of electrolyte thermal diffusivity,

κ - electrolyte conductivity,

T- electrolyte temperature,

c_p- specific heat with constant pressure,

Formulated equation system (7)-(12) is the principal system of equations for the analysis of an axially-symmetrical flow of the electrolyte and hydrogen mixture flow through the interelectrode gap.

The solution of equation system (7)-(12) will enable to define distributions of velocities, pressures and temperature in the interelectrode gap. The obtained formulas defining the temperature distribution in the gap will be utilized for determination of the workpiece (WP) shape evolution (anode) on the basis of equation (4).

Solutions of equations (7)-(12) should satisfy boundary conditions with regard to :

- pressure and velocity components:

$$\begin{aligned} v_x = v_y = 0 \quad & dla \quad y = 0, \\ v_x = v_y = 0 \quad & dla \quad y = h, \\ v_\theta = 0 \quad & dla \quad y = 0, \\ v_\theta = \omega_\theta R(x) \quad & dla \quad y = h, \\ p = p_z \quad & dla \quad x = x_z \end{aligned} \tag{13}$$

-for temperature:

- on the walls: $T = T_s$ dla $x \geq x_w$ i $y = 0$ oraz $y = h$

- on the inlet: $T = T_w$ (14)

here: p_z – pressure on the interelectrode gap outlet,

x_z – coordinate of the interelectrode end

x_w - coordinate of the interelectrode beginning

T_s - temperature of electrodes, T_w – temperature on the inlet,

A – vibration amplitude,

ω_z- vibration frequently,

ω_θ - angular velocity.

When integrating motion equations (9) – (10), one can obtain formulas defining velocities and pressures within the interelectrode gap.

$$v_x = \frac{3Q}{\pi R h^3}(hy - y^2) + \frac{\rho}{\mu}\left[\frac{1}{12}\frac{\omega^2 RR}{h^2}(y^4 - h^3 y)\right] \quad (15)$$

$$v_y = \frac{V}{h^2}(3hy^2 - 2y^3) \quad (16)$$

$$v_\theta = \omega R\frac{y}{h} \quad (17)$$

$$p(x) = -\frac{6\mu_e Q}{\pi h^3}(A_x - A_z) + p_a, \quad A_x = \int\frac{dx}{R}, \; A_z = \int\frac{dx}{R_z} \quad (18)$$

Dependencies (15)-(18) describe velocity and pressure distributions in the mixture laminar flow through the gap, with a random profile of surfaces limiting the flow. The assumption of specific geometry of the axially-symmetrical surface leads to accurate definition of velocity and pressure distributions.

Distribution of void fracture ß was determined from the mass balance of hydrogen, given off on the cathode.

When integrating equation (8) across the gap

$$\frac{1}{R}\frac{\partial}{\partial x}\left(\rho_H R\int_0^h v_x dy\right) + \rho_H v_y\Big|_0^h = j\eta_H k_H \quad (19)$$

and, next, accepting the assumption that $\beta = \beta(x)$ one can obtain, after transformations:

$$\frac{\partial}{\partial x}\left(\frac{p}{T}\beta\right) = \frac{2\pi\eta_H k_H}{\mu_H Q} jR \quad (20)$$

whereas: β - void fracture, $\rho_{Ho} = \frac{\mu_H p}{R_H T}$ - hydrogen density, η_H - current efficiency of gas emission, k_H - hydrogen electrochemical equivalent, R_H - hydrogen gas constant, μ_H - hydrogen molar mass.

Solution to equation of the machined surface shape evolution (4) was based on the method of successive approximations in combination with the time step method [6,7,20,21].

3. Numerical model of ECM process

This problem is accounted for according to a successive approximation method for all used numerical schemes using at the same time the time steps method [6,7,20,21].

Energy equation (12) has been solved numerically with the use of finite difference method replacing the temperature derivatives with algebraic expressions.

Simplified algorithm of a mathematical model solution is presented in fig. 2.

4. Conclusions

Calculations were performed for shaping rotary electrodes with spherical surface profiles. The supply system ensures the electrolyte fixed flow rate in the interelectrode gap. Passivating electrolyte was accepted for calculations. Calculations had been performed until a quasi – stationary state was reached.

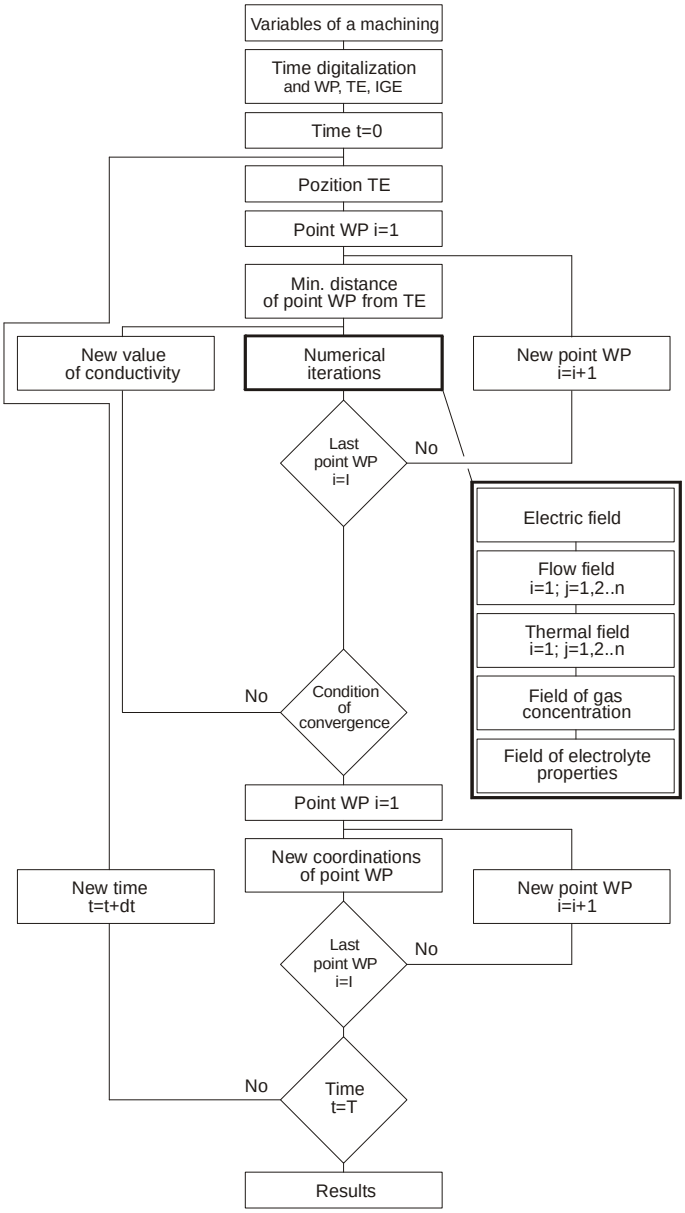

Fig.2. ECM computer simulation algorithm

For calculations the following, machining parameters were accepted:

Initial gap h_o	0.2 mm
Speed of move forward of TE V_f	0.01 mm/s
Interelectrode voltage U	15 V
Volume rate Q	3 l/min
Pressure p_z	0,1 MPa
Rotational speed of WP n	0, 1200 obr/min

The obtained results have been illustrated in charts (Fig.3-8) which demonstrates distributions of: interelectrode gap height h, current density j, temperature T_m, void fraction β, velocity V_m, and pressure p along the interelectrode gap (IEG).

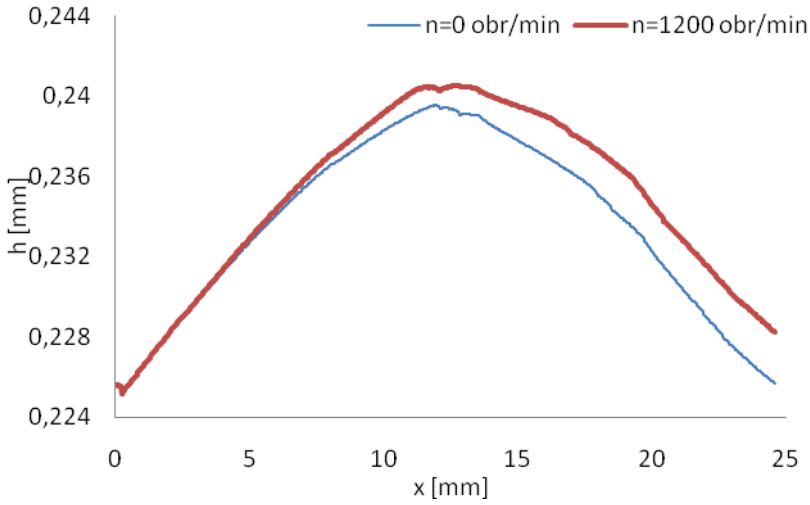

Fig. 3. Distribution of gap height h along IEG

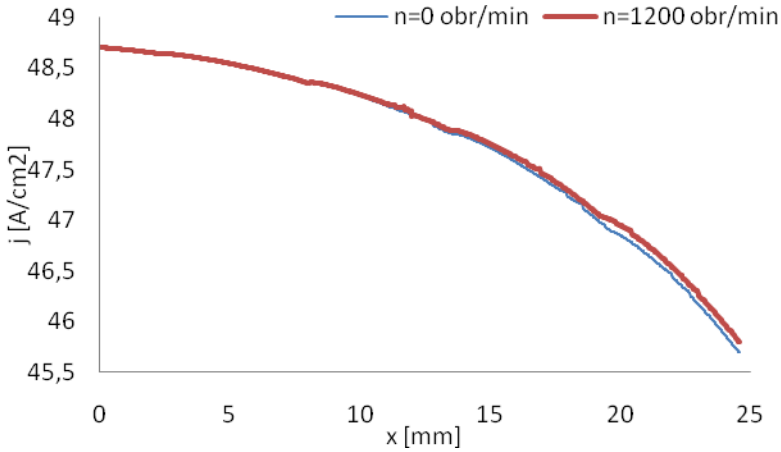

Fig. 4. Distribution of current density j along IEG

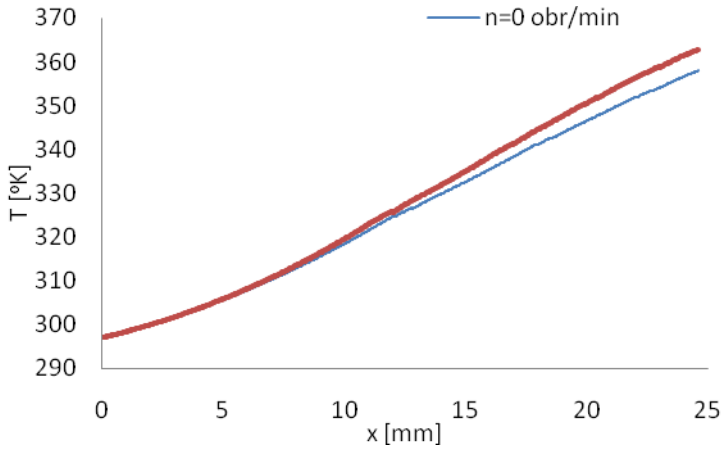

Fig. 5. Distribution of average temperature T along IEG

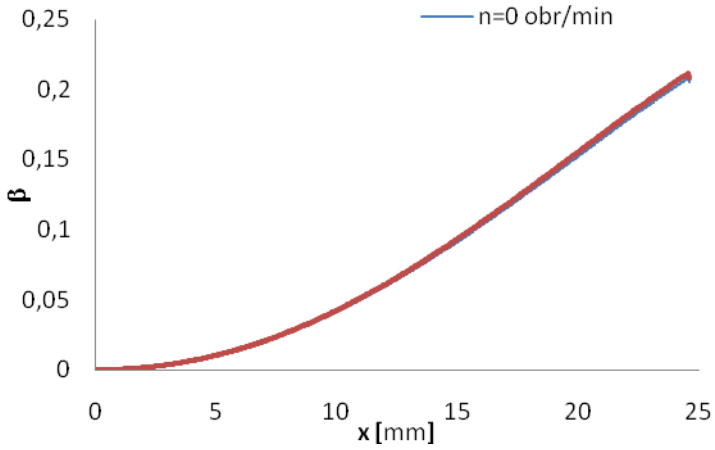

Fig. 6. Distribution of void fraction β along IEG

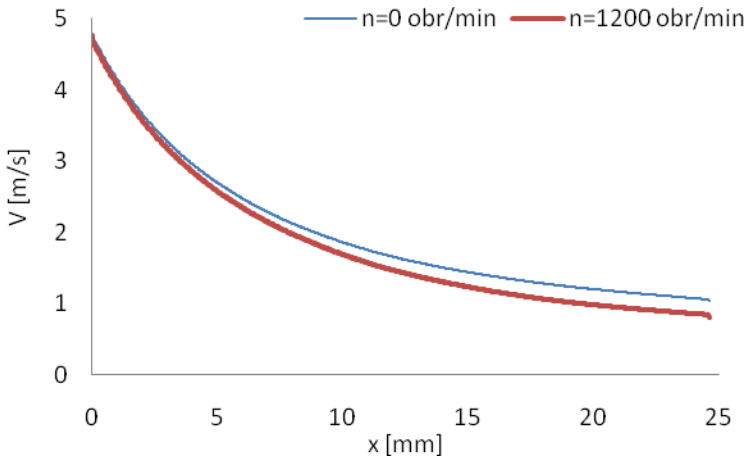

Fig. 7. Distribution of average velocity V along IEG

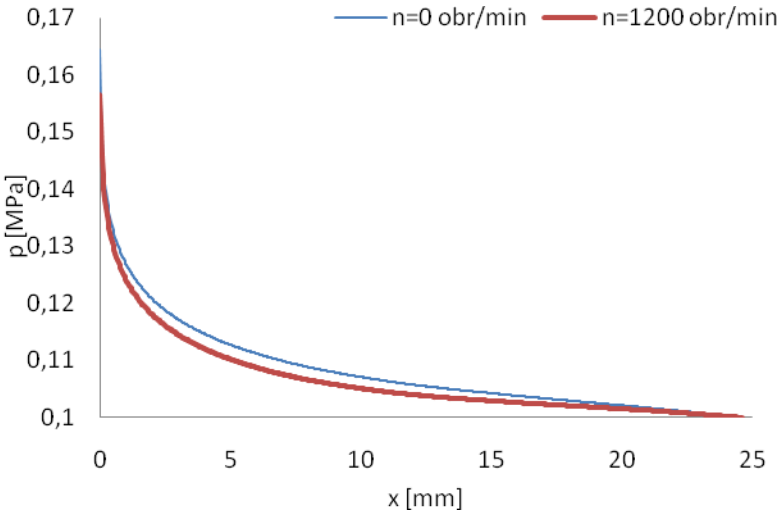

Fig. 8. Distribution of pressure p along IEG

The above presented charts allow for formulation of the following conclusions:

- Local changes of the interelectrode gap thickness are a result of different dissolution velocities as well as dynamically changing physical conditions within the interelectrode gap.
- Distribution of current density along interelectrode gap (IEG) depends on the gap section field and frequently changing physical parameters of the flow caused by electrochemical dissolution
- Temperature of the electrolyte and hydrogen mixture increases gradually along the interelectrode gap during the set machining time
- Distribution of void fracture in the interelectrode gap (IEG), determined from equation of the hydrogen flow continuity, demonstrates changes in proportions of hydrogen volume in the electrolyte along the way of the mixture flow.
- Distributions of pressure and the mean velocity along the gap is caused mainly by changes of the interelectrode gap (IEG) section field in the set machining time.
- It should be noticed that the rotational speed of the workpiece (WP) have a specially large influence on the gap height.

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