Some problems of surface roughness in electrochemical machining (ECM)

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Abstract

Electrochemical Machining (ECM) provides an economical and effective method for machining high strength, heat-resistant materials into complex shapes such as those with high material removal rate without tool wear and without inducing residual stress. ECM is performed without physical contact between the tool and the workpiece in contrast to the mechanical machining. Therefore, surface layer formed during ECM process characterizes with no mechanical distortion, compressive stresses, cracks or thermal distortions.

This paper presents some features of ECM processes, such as the effect of heterogeneous structure of material workpiece and the influence of hydrodynamic instability of anode boundary layer on the surface roughness. A mathematical model was developed to simulate the evolution of surface profiles during electrochemical machining of alloys with the heterogeneous structure. Results of computer simulation and an analysis of the effects of various ECM factors and the structure of the workpiece material, on the surface roughness and its parameters is done. The experimental investigations confirmed the effect of hydrodynamic instability of boundary layer on micro topography of machined surface done.

1. Introduction

Electrochemical Machining (ECM) is an important manufacturing technology in machining difficult-to-cut materials and shaping complicated contours and profiles with high material removal rate without tool wear and without inducing residual stress. The machining is based on controlled anodic electrochemical dissolution process in which the workpiece is the anode and the tool is the cathode of an electrolytic cell. In the ECM process, a low voltage (8-30V) is normally applied between electrodes with a small gap size (usually 0.2 to 0.8 mm) producing a high current density of the order of (10 to 100 A/cm\textsuperscript{2}), and a metal removing rate ranging from an order 0.1 mm/min, to 10 mm/min. Electrolyte (typically NaCl or NaNO\textsubscript{3} aqueous solutions) is forced to flow through the inter electrode gap with high velocity, usually more than 5 m/s (with Reynolds number of the order of 10\textsuperscript{3}-10\textsuperscript{5}), to intensify the mass/charge transfer through the sub layer near anode and to remove the sludge (dissolution products e.g. hydroxide of metal), heat and gas bubbles generated in the gap. 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, such as hardness, elasticity and brittleness. Various variants of ECM like: electrochemical sinking, ECM with numerically...
controlled tool electrode movement, ECM with orbiting tool electrode, pulse electrochemical machining (PECM), electrochemical smoothing, electrochemical debarring are used in industrial practice. It has been applied in diverse industries such as aerospace, automotive and electronics to manufacture airfoils and turbine blades, dies and molds, surgical implants and prostheses, artillery projectiles etc. [1-4].

The main objective of ECM is to achieve the required shape of workpiece within a given tolerance on the shape and dimensions and surface roughness.

2. Surface layer integrity after ECM

ECM is performed without physical contact between the tool and the workpiece in contrast to the mechanical machining, and without strong heating in the machining zone in distinction to the methods like EDM. Therefore, no surface metal layer with mechanical distortion, compressive stresses, cracks, and thermal distortion forms in ECM. ECM is often used even for removing a defective layer, which has been formed in EDM, with the aim to improve the surface integrity. However, sometimes the intergranular attack occurs in ECM. This may reduce the performance of machined parts. The workpiece surface roughness after ECM depends on many parameters: electrolyte composition and temperature, current density, etc.

The anodic dissolution of metals is rather structure-sensitive method. We have already touched on the effect of alloy structure on the anodic dissolution rate. This factor is of importance also for the surface finish after ECM. For example, for a series of titanium-base alloys it has been shown that the preliminary heat treatment of alloys, leading to the fine-grained structure, assure low roughness after ECM. The operating conditions, which give large-grained structure, lead to the high roughness after ECM. A decrease in the grain size of steel by the heat treatment leads to a decrease in the surface roughness of the workpiece. This is especially pronounced at not very high electrolyte flow rates. An increase in the flow rate leads to a decrease in the roughness, and at velocity > 15 m/s, the effect of grain size on the roughness becomes insignificant.

In the potential range of the limiting current and in the post-limiting current region, the metal is covered with an oxide film that hampers the direct passing of metal cations from the crystal lattice into the solution. The suppression of crystallographic etching by this film and the preferred dissolution of surface projections lead to the production of bright or even polished finish.

After the metal dissolution in the region of limiting or over-limiting current, the macro-defects of striation type are often observed at the surface. This is associated with the diffusion control of metal dissolution in this potential range, when the dissolution rate is determined by the distribution of local electrolyte flow rates. Any flow non-uniformity or the spray formation (for example, near a particle of poorly soluble carbide, which projects from the surface, or near a pit formed, when this particle is fallen out) makes a mark on the bright metal surface.

3. Mathematical modeling of surface roughness evolution in the course of ECM

A non-uniform distribution of material removal rate on machining anode results in changes of the workpiece shape and its surface roughness.

Prediction of the final shape of the anode requires, a moving boundary simulation where, at each time step, the distribution of velocity dissolution on the workpiece surface needs to be determined. This rate is equal to velocity of anodic dissolution $V_n$ (Fig. 1), which is normal to surface anode and can be determined from Faraday’s law as:

$$V_n = K_a i_a$$

where: $i_a$ is current density on anode, $K_a$ is the coefficient of electrochemical machinability which is equal to the volume of material dissolved from the anode per unit electrical charge– in general it is the function of, among others, current density. Distribution of current density is determined by the electrical field between both electrodes: tool-cathode and workpiece-anode. Electrical potential $u$ is described by equation and boundary conditions, which are shown in the frames on Fig. 2.

Most materials used in practice have a polycrystalline structure and consist heterogeneous components. Each phase in these materials has a certain characteristic polarization behaviour and coefficient of electrochemical machinability. Electrochemical properties of grains of the same phase can also be different as a result of differences in crystal orientation and density of dislocations.

An essential feature of variation in the surface roughness of alloys involving two or more phases is a difference in the electrochemical equivalents along with the difference in polarization values that may be incomparably greater than the difference in polarization on different crystal planes of the same metal. The latter is of particular importance, when the...
difference in polarization is caused by different tendency to the passivation. In the extreme case, one phase of the alloy may dissolve at a very small polarization (negligibly small as compared with the voltage across the electrodes), and the second phase may remain in the passive state and almost not dissolve in a very wide range of anodic potentials. Electrochemical machining characteristic of heterogeneous structure is shown in Fig. 1. The figures show the presence of grains of different phases along with dislocations in the microstructure of the material.

A mathematical model was developed for the smoothing process of the heterogeneous structure of alloys with a random surface profile. The software has been developed for computer simulation of ECM of material which consisted of two different phases with electrochemical properties \( K_v(a), E(a) \) and \( K_v(b), E(b) \).

Three cases of dissolution rate distribution are usually distinguished as follows \([2, 6, 7]\):

1. by means of the electric field between the rough electrode under study and perfectly smooth (plane) counter electrode \( \frac{\partial}{\partial x} - \kappa \nabla u \).
2. by the electric field distribution and electrochemical polarization of the electrode involved (secondary distribution); and
3. by the concentration distribution of the electrolyte components in the near-electrode diffusion layer (tertiary distribution).

In first approximation the following assumption have been made in developing a mathematical model of the ECM process with a tool electrode system shown in Fig. 2:

- Electrolyte flow rate between electrode and workpiece is high enough to neglect changes in electro conductivity of electrolyte,
- Dissolution product does not affect electrolyte properties,
- Anode-workpiece surface is uniformly covered by electrolyte,
- Electrical field in the gap is quasi-stationary
- Primary distribution of electrical potential in the gap has been considered, i.e. polarization of electrodes is constant and equal some average value

According to electrochemical shaping theory, in the tool electrode coordinate system \( x, y, \) and \( z \), the evolution of the shape of the workpiece \( Z(x, y, t) \) can be described as \([2, 4, 5, 6]\):

\[
\frac{\partial Z}{\partial t} = K_v f_A \sqrt{1 + \left( \frac{\partial Z}{\partial x} \right)^2 + \left( \frac{\partial Z}{\partial y} \right)^2} - V_t \tag{2}
\]

where: \( K_v = K_v(f_A) \), coefficient of electrochemical machinability, \( f_A \) - current density on the surface of anode.

At the beginning of machining: \( t = 0, z = Z(x, 0) \), describes the initial shape of the workpiece i.e. profile of the surface roughness

In the region where concentration gradient can be ignored, Ohm’s law in differential form describes current density \( i \) in the electrolyte:

\[
\dot{i} = -\kappa \nabla u \tag{3}
\]

Based on electrical neutrality of the electrolyte, the electric field is source less and has quasi-stationary nature, in which a time plays role of parameter, we get the well known form of the equation describing distribution of electrical potential \( u \) in electrolyte:

\[
\nabla^2 u = 0 \tag{4}
\]

Under the given assumption, changes of conductivity of electrolyte in the gap between electrodes due to heating and gas generation are neglected, and Eqn. 4 is transformed into Laplace equation:

\[
\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} = 0 \tag{5}
\]

The boundary conditions for equations (5) are given by the state of the system on the electrodes. Assuming perfectly conducting electrodes, which are connected with the external source of voltage \( U \), the boundary conditions in this case can be given as follow:

- \( u = E_c (t) \) on the anode - tool;
- \( u = U(t) - E_a (t) \) on the cathode - workpiece;
- \( \frac{\partial u}{\partial n} = 0 \) on the insulating walls.

The anodic potential \( E_a \) and the cathodic potential \( E_c \) depend on current density, and are determined by the sum of both the concentration and the activation overpotential for each electrode, from polarization curves.

To complete of the systems of Eqs. (2)-(5), the relationship described electrode relative movement and distribution of voltage pulses in time (in the case of Pulse ECM) have been added.

For a numerical solution of the problem, a small time interval \( \Delta t \) needs to be selected so that the interfaces can be regarded as stationary when calculating the electrical field and current density on the anode during this time interval \( \Delta t \). After solving the corresponding problem for a known boundary, one can find the position of the boundary at the next instant given by \( t+\Delta t \). Then the problem is solved with a new boundary.

A computer-based approach was developed to model and analyze the smoothing process during ECM.

A program has been developed to simulate the generation of surface profiles with time during ECM. To solve the governing partial differential equations for simulation the ECM shaping problem, the finite difference method has been used.

For example, the results of simulation of changes of surface profile during ECM process for the homogenous and heterogeneous material with \( K_v(a)=1.5 \text{ mm}^3/\text{Amin}, E(a)=2.0 \text{ V} \)
The heterogeneous structure appears in the machined profile and roughness increases in time to some asymptotic value, which depends on the difference between electrochemical properties of phases (Kv and E), electrical conductivity of electrolyte and the machining parameters such as feed rate and working voltage. The asymptotic value of Rz can be estimated as following:

$$R_z = \frac{K_v}{V_f} [(U - E_v) K_{va} - (U - E_f) K_{vb}]$$

The major factor, which have significant effects on the final surface roughness after ECM is feed rate.

As shown in Fig.7 and Eq. (6), the increasing of feed rate, which is proportional to current density, result in decreasing of machined surface roughness. The increase in the current density is among the simplest and most widespread expedients of increasing the machined surface integrity. It should be noted that a simultaneous increase in the productivity and integrity of the machined surface is a unique property of ECM. However, in the ECM of the large-sized workpieces, it may be difficult to produce the high current densities. In these cases, it is worthwhile to use the electrolytes yielding low roughness at rather low current densities, for example, Na2SO4.

4. The effects of hydrodynamic flow on surface topography

The main advantages of ECM processes are often offset by the poor dimensional control and process stability resulting from the complex and stochastic nature of the processes in the electrode gap. The examples of defects on dissolved surface are shown in Fig.8.

Fig.8. The examples of hydrodynamic defects of electrochemical machined surfaces. The electrolyte flow direction is indicated by the arrows.
The character of appeared features allowed to made of conclusion that these defects caused of hydrodynamic of boundary layer on anode (workpiece). In particularly it is the effect of coupling of hydrodynamic and electrochemical instability and topography of surface.  

It has been established that spatially coherent and temporally evolving vortical structures, popularly called coherent structure, has significant influence on surface micro-topography generated during electrochemical shaping. Extensive experimental and numerical efforts were devoted to this problem [10-13] and several models of the coherent structures were proposed, such as hairpin vortex packets [13]. In the turbulent boundary layer the stream wise velocity field in the sublayer and buffer regions is organized into alternating narrow streaks of high- and low-speed fluid that are persistent and relatively quiescent most of the time. The majority of the turbulence production in the entire boundary layer occurs in the buffer region during intermittent, violent outward ejections of low-speed fluid and during inrushes of high-speed fluid at a shallow angle toward the wall. The complete cycle of lift-up of fluid, oscillation, ejection and sweep motion is usually called the bursting phenomenon. During this near-wall bursting turbulence-production process, the passage of a hairpin vortices has been generated as shown schematically in Fig.9.

\[ \lambda_w = C S \text{Re}^{-0.75} \]  

where: \( \text{Re} = \frac{2 S w}{v} \) is the Reynolds number, \( w \) is the mean flow velocity, \( S \) is the gap, \( v \) is the kinematic viscosity and \( C \) is experimental constant.

The flow is driven by a pump (max. pressure 1.5 MPa) and the flow rate is control by valves and a flow meter. The experiments were performed with in various of electrolyte flow rate and electrical parameters of machining according to experiment design. The ECM carried out with using water solution of NaCl and NaNO₃ for material such as: die steel, stainless steel, superalloys and titanium alloys.

During the electrochemical machining of solid black surface
film was formed on the specimen surface. The adhesion of this surface film depends on the type of electrolyte. The use of concentrated NaCl-electrolyte leads to a surface film, which could be easily washed off with water. The surface morphology of the substrate after ECM is illustrated with Figs.12, where the wave structures on the surface film are exhibited.

The plot of the wave length vs. Reynolds number of flow electrolyte is shown in Fig.15. The wave length were determined as \( \lambda = \frac{L}{n} \), where \( n \) is number waves on distance \( L \).

By regression analysis on experimental values, the experimental relationship between wave length in pattern \( \lambda_w \) and Reynolds number is as following:

\[
\lambda_w = 4.07 \times 10^3 \cdot Re^{-0.72}
\]

(8)

for \( S \) (from 0.3 to 2 mm) and \( Re \) (from \( 2 \times 10^4 \) to \( 8 \times 10^4 \)).

The exponent index of experimental relation (-0.72) is closed to exponent of estimated relation based on model of coherent structure of turbulent boundary layer. It lead to conclusion that structure of pattern on machined surface corresponding with coherent structure in the turbulent boundary layer.

The coupling of hydrodynamic and electrochemical processes can lead to the possibility of specific hydrodynamic-electrochemical resonance in a system, "coherent structures of the boundary layer - the anodic dissolution – roughness" [5, 8, 9].

In certain conditions of electrochemical machining, the result of coupling hydrodynamic fields with processes of diffusion, depassivation and anodic dissolution is appeared as the waves of pattern and ripples structure formation on the metal surface, i.e. not only on surface film (oxides, salt etc.).

The topography of surfaces machined at appearance of hydrodynamic-electrochemical resonance is shown in Fig.14.

This phenomenon has an analogy in the formation of waves/ripples on the border of the loose and liquid/gas medium as shown in Fig. 15.

5. Conclusions.

1. The modeling and computer simulation of electrochemical dissolution of heterogeneous material has been developed to understand the basic mechanism of evolution surface profile in ECM. In the first stage of machining there is smoothing of surface and the surface roughness decreases. After some time the effect of differences in properties between phases, dominates the geometrical factor of surfaces and roughness increases in time to some asymptotic value.

2. The experimental investigations confirmed that geometrical features of surface structure after ECM corresponding with coherent structure of boundary layer in turbulent flow of electrolyte. In some conditions of ECM, the specific hydrodynamic–electrochemical resonance can be appeared, which effected in topography of machined surface.

References