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Ultrasonic Enhancement of an Electrochemical Machining Process

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Abstract: - The paper deals with the ultrasonic assistance of an electrochemical process. There are presented and discussed some experimental investigations obtained on a laboratory prototype, at two ultrasonic frequencies. The results, expressed in the evolution of current, voltage and electrolyte temperature during the process, prove the favourable effect of the ultrasonic field in electrochemical depassivation in order to improve the perfomance of the electrochemical machining process.

Key-Words:- Electrochemical machining, ultrasonic processing, hybrid machining processes, depassivation

1. Introduction

In the vast and complex field of electrotechnologies, electrochemical machining technique (ECM) represents a relatively new and important method of advanced material processing, where the traditional machining technologies become unable. ECM is based on removing metal by anodic dissolution, and is characterized by some indices of performance such as: higher dimensional precision, higher productivity, reduced tool wear, no residual stress in the workpiece, comparatively with the conventional machining techniques, [1,2,3,4,5].

The ECM techniques allow to accomplish some difficult machining operations (complex shaping, boring, turning, milling, polishing, etc), without a direct contact between the tool and the workpiece, with high stock removal rates, regardless of the mechanical properties of the workpiece. The workpiece can be done from various materials such as alloys, metal-ceramic composites, characterized by improved strength, wear, corrosion and heat resistance.

The ECM technique is unavoidably asociated with the specific process of passivation, that results in a progressive reduced action of the machining process. Because the passivation effect has such a major influence on the ECM process, in industrial applications forced-depassivation measures are to be taken by various methods of permanently activating the gap between the tool and the workpiece.

In order to remove the layers of oxides and other compounds from the anode surface, and thus to improve the productivity of ECM process, various methods of so-called "hybrid (cross) machining processes", in which ECM is assisted by various other machining techniques, have been broadly presented and analyzed, in technical literature [5].

In the present paper, an experimental study of the ultrasonic-based depassivation process and its benefits related to an ECM proces are presented and discussed.

2. Basics of ECM process

Electrochemical Machining (ECM) for conductive materials is based on anodic dissolution process developed in an electrolytic cell, in the presence of an imposed electric field, Fig. 1. The metalic workpiece (WP) is connected to the positive terminal of the power source, thus being anode, and the tool electrode (TE) is connected to the negative terminal of the power source, being cathode. Both of the electrodes are immersed into an electric conductive solution, termed as electrolyte (EL).

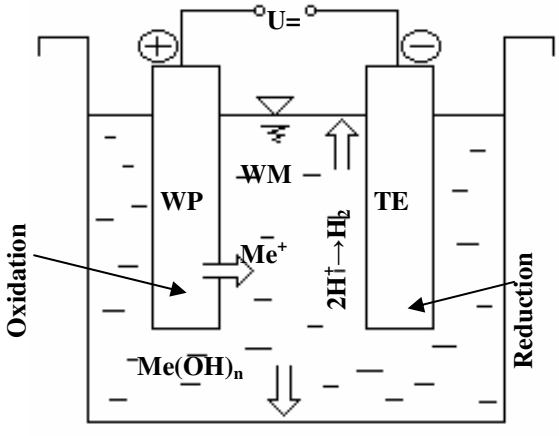


Fig. 1. The principle of ECM process.

In order to ensure the development of the chemical reactions that lead to the progressive erosion of the workpiece, i.e. oxidation (de-electronation) at the anod and reduction (electronation) at the cathod respectively, the applied voltage on the electrolytic cell (usually 8-30 V) must exceed the sum of the decomposition voltages at the two electrodes and the voltage drop across the inter-electrode gap.

Two energy conversion mechanisms are involved in conjunction with an electrochemical process: an electro-chemical energy conversion, that occurs in the limit layer associated with the electrode-solution interface, and an electro-thermal energy conversion, developed in the bulk of electrolyte, by Joule effect, [1, 2, 3].

The tool-electrode acts as an element designed to transfer the energy required to initiate and to maintain the erosive action, as well as an information carrier with regard to the control and the placement of the erosive action on the surface of the workpiece.

During the ECM process, the tool-electrode does not suffer any wear, while the electrolyte is subjected to some major alterations of its properties (impurities, heating, pH-changing, etc.), that imposes to take measures for reconditioning it.

The whole physical and chemical transformations that occur in the electrochemical cell result in a so-called "passivation state". A metal can be considered as electrochemically passive, when it cannot be difussed by means of positive ions into the solution, although it is anodic polarized at a positive potential greater than its decomposition potential. Therefore, the passivation effect can negatively influences the productivity of the ECM process.

The depassivation can be achieved by means of some specific actions:

- Chemical depassivation, with the help of some chemical elements;
- Hydrodynamic depassivation, with forced circulation of the electrolyte in the inter-electrode gap;
- Mechanic depassivation, by the action of an abrasive tool upon the passivate film;
- Electric depassivation, by periodically changing the polarity of the applied voltage;
- Compound methods: ECM with electrical discharge machining (EDM) assistance, or ECM with ultrasonic machining (USM) assistance , [5].

In order to improve the process performance, the ECM equipment must be able to precisely control the operating parameters, such as: active inter-electrode gap, supply voltage, working current, electrolyte temperature, pH and flow velocity, respectively, etc.

3. The influence of the ultrasonic field on the ECM process

The use of ultrasound energy in a series of industrial applications is related to the characteristic features of ultrasonic waves: relatively small wave-length, very high acceleration, leading, focussing and spreading facilities, as well as the specific interaction with the propagation/working environment. The most important ultrasonic propagation effect in liquid media is known as ultrasonic cavitation, [4, 6].

In principle, two basic techniques of ultrasonic assistance of ECM processes are usually mentioned in literature, [4]:

- *Direct ultrasonation* (vibration) of the electrode, using a concentrator-type ultrasonic block;
- *Indirect ultrasonation*, by immersing the electrochemical cell into an ultrasonic activated liquid medium (ultrasonic bath).

The benefits of ultrasonic intensification of electrochemical processes have been pointed out by a lot of theoretical approaches and experimental investigations, [5-10]. Ultrasonic assistance of ECM process is based on the effects on properties of workpiece material and working media, resulting in two specific interactions, that lead to an increase of surface dissolution, and electrochemical reaction rate, [5].

It is generally ascertained that in the progress of electrochemical processes the ultrasounds positively influence the phenomena, providing the following benefits, [6,7,8,9]:

- acceleration of the reaction (catalytic effect);
- improvement of characteristics of the electro-deposited layer;
- control of passivation;
- enhancement of diffusion processes, both in liquid-phase and in solid-phase as well.

Particularly, in electrochemical processes with soluble anods, where the atoms pass from the metal into the solution as positive charges (cations), the ultrasonic field influences in a complex manner the thermodynamic behaviour of the metal-electrolyte system, and the electro-kinetic factors as well.

The amplification effect of mass and electric charge transfer rate in ultrasonic stirred solutions is dependent of the amplitude and of the frequency of vibration respectively. From experimental data, empirical relationships have been formulated for the

average critical (limit) current density, j_{avg}, and for the average mass-transfer coefficient, k_{Mavg}, [3].

$$j_{avg} = \frac{1{,}11 D_j^{2/3} \cdot \xi^{0,7} \cdot \upsilon^{0,7}}{\left(\eta/\gamma\right)^{0,36} \cdot d_e^{0,3}}$$
$$k_{Mavg} = \frac{0{,}808 D_j^{2/3} \cdot \xi^{1/3} \cdot (2\pi \cdot \upsilon)^{1/2}}{\left(\eta/\gamma\right)^{1/6} \cdot d_e^{1/3}} \quad (1)$$

where: D_j – the diffusion coefficient, ξ – the amplitude of vibration, ν – the ultrasonic frequency, η – the dynamic viscosity of the electrolyte, γ – the mass-density of the electrolyte, d_e – the diameter of the electrode.

The main effects of an ultrasonic activated ECM process, are comparatively presented in Fig. 2, in terms of the critical current density, j, [10]. The two anodic polarisation curves have been experimentally determined, in two cases of direct ultrasonation: without and with ultrasonic intensification, respectively. It can be observed an increase of the electrode potential of the metal (anode), V_ε, and of the critical (limit) current density as well.

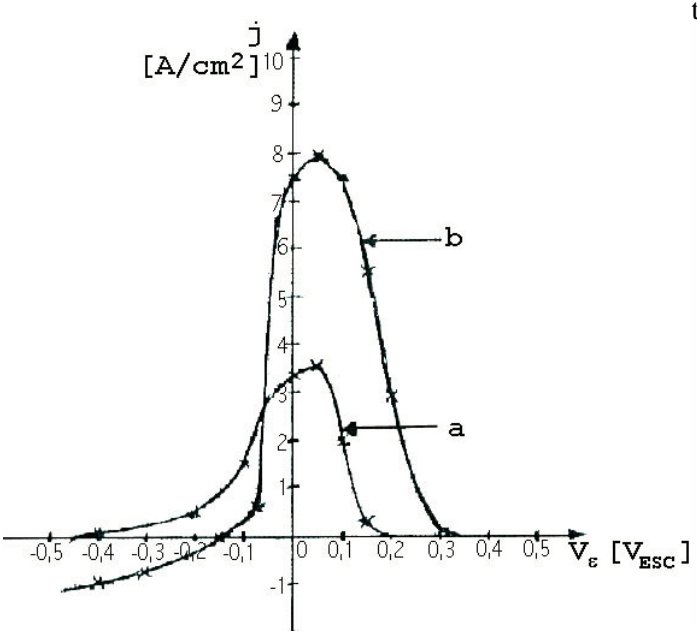


Fig. 2. The anodic polarisation curve for Ni: a) without ultrasonic field; b) in ultrasonic field.

This can also represent a fairly reason for a succesful use, in certain cases, of ultrasonic intensification in order to reduce the passivation and thus to increase the metal-removal rate.

4. Experimental results

In order to determine quantitatively the influence of the ultrasonic field on the performance of ECM process, a laboratory experimental set-up was used. The installation is composed by the following functional units, Fig. 3:

- the ECM system, with the adjustable DC power source, and the electrolytic cell with glass walls; as electrolyte (WM) a sodium chloride (NaCl - 20%) solution in water was used; a steel sheet (OL 37) as the workpiece (WP), and a copper blade as tool-electrode (TE) were also used;
- the electro-ultraacoustic conversion system, composed by an electronic generator (EG), the piezoceramic ultrasonic transducer (TGUS) and the ultrasonic cleaning bath (UB). As ultrasonic working medium in the bath, tap water has been used. Actually, two ultrasonic baths have been used: one, at a resonant frequency of 20 kHz, and the other at a resonant frequency of 56 kHz.

The electrolytic cell was maintained immersed in the ultrasonic bath during the process, in order to receive the vibration energy into the bulk of electrolyte through the electrochemical cell glass walls.

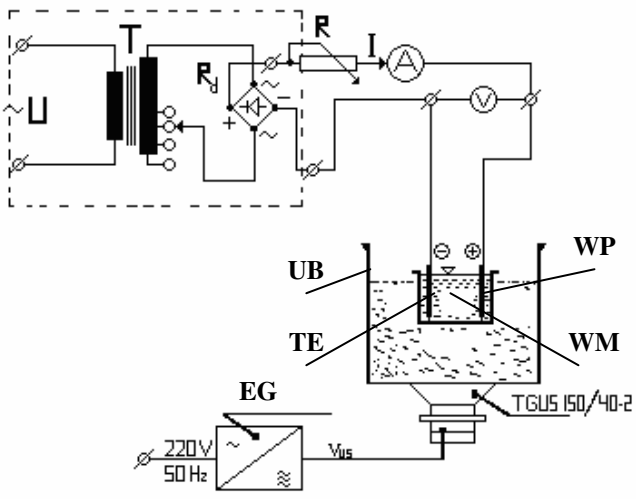


Fig. 3. The experimental set-up.

Comparatively experimental investigations have been done. The ECM process have been investigated without and with ultrasonic intensification, in the following identical operation conditions:

- the same composition, concentration and volume of electrolyte;
- identical workpiece (material, geometry and dimensions);
- the same tool-electrode and active gap;
- the same processing time (10 min);
- comparatively the same ultrasonic powers.

The experiments were conducted at two reference values of working current (10A and 15 A respectively), each of them in three distinct cases:

- ECM without ultrasonic assistance (control sample);
- Ultrasonic assisted ECM, with operation frequency at 20 kHz, and measured transducer excitation active power of 37 W;
- Ultrasonic assisted ECM, with operation frequency at 56 kHz, and measured transducer excitation active power of 80 W.

The current density during experiences was determined between 0,6 to 0,8 A/cm^2.

The time evolution of the main process parameters is depicted in the following figures:

- the imposed working current in the electrochemical cell, *I(t)* , in Fig. 4;
- the voltage drop across the electrochemical cell, *U(t)*, in Fig. 5;
- the electrolyte temperature, *T(t)* , in Fig. 6.

In Table 1 are presented the determined theoretical mass of metal removed (M) and the mass-productivity (MP) in all of the three cases experimentaly investigated, for the two currents. The theoretical mass was calculated with the following relationship, based on the Faraday's law:

$$M = K_{Fe} \cdot \int i(t) \cdot dt = K_{Fe} \cdot \sum_{n=1}^{n=10} I_n \cdot t_n = \frac{A_{Fe}}{v_{Fe} \cdot F} \cdot \sum_{n=1}^{n=10} I_n \cdot t_n \qquad (2)$$

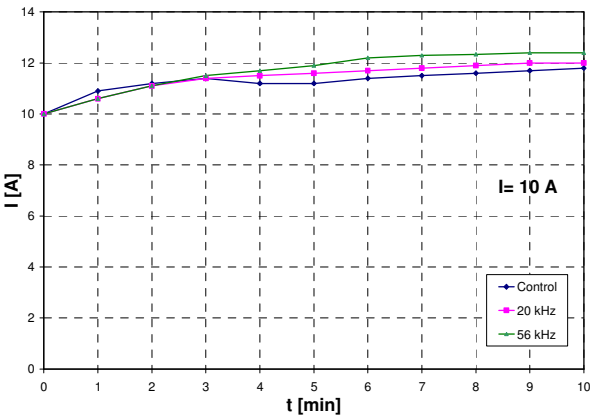
The mass-productivity is therefore given by:

$$MP = \frac{M}{t_p} \qquad (3)$$

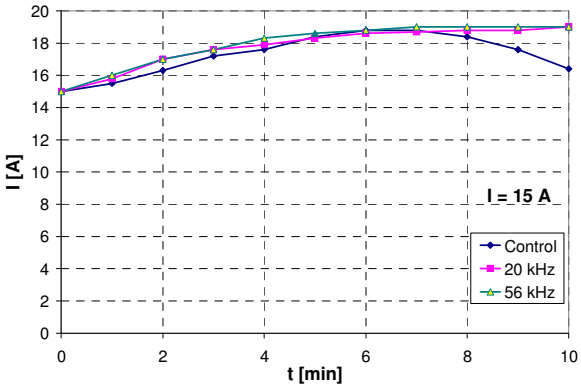
where:

K_{Fe} is the electrochemical equivalent for iron;
$A_{Fe} = 55{,}85$ [g], is the atomic weight of iron;
$v_{Fe} = 2$, is the valence of iron;
F = 96484,64 [C], is the Faraday number;
$t_p = 10$ *[min]* total processing time;
$n = 1 \ldots 10$ current index for the sum.

As can be seen from the diagrams of Fig. 4, in the case of ECM without ultrasonic assistance, in the first interval of ECM process, the current tends to increase due to the heating of the electrolyte and thus of increase of its conductivity. In the second interval, the current tends to decrease due to the passivation, that is more clearly at the greater working current (15A). In the cases of ultrasonic assisted ECM, the curent is monotonously rising, due to the favourable effect of ultrasonic-aided depassivation, that is more clearly observed at the frequency of 56 kHz.



a). I = 10 A

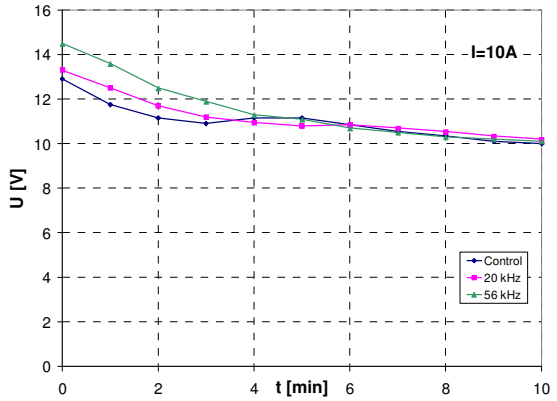


b). I=15 A

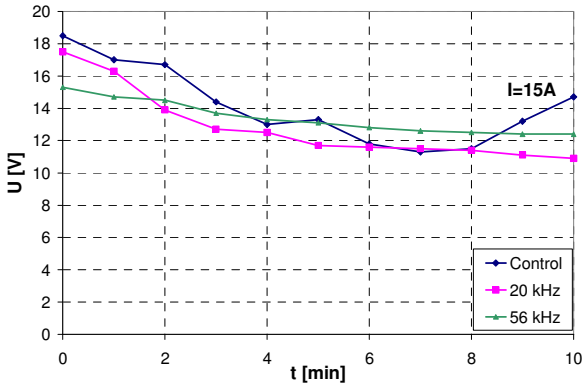
Fig. 4. The current evolution during the ECM process.

The voltage drop across the electrolytic gap shows a negative slope, due to the heating of the electrolyte. It can be observed a slight increase of the voltage drop, due to the passivation effect, more obviously in the case b), where the working current was I = 15 A. In fact, the current evolution, depicted in Fig. 4, is aproximatively followed by the voltage evolution, depicted in Fig. 5. The greater ultrasonic frequency has a more favourable effect on the process, that is reflected in the current and the voltage evolutions during the machining.

The temperature diagrams show a progressive heating of the electrolyte during the ECM process, due to the Joule effect of the current through the inter-electrode gap. As can be seen, the current influences the electrolyte temperature reached at the end of the process time, i.e the grater working current (15 A) leads to a higher final temperature.



a). I=10A



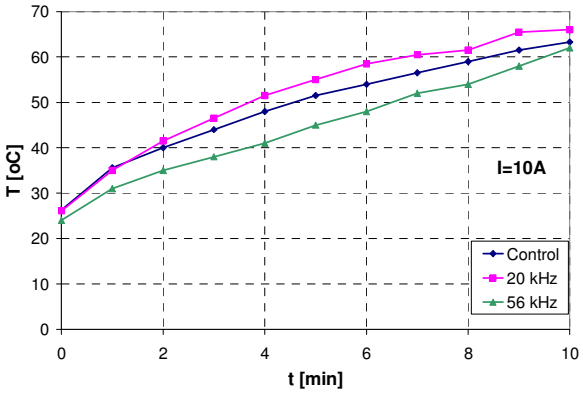
b). I=15A

Fig. 5. The voltage drop evolution during the ECM process.

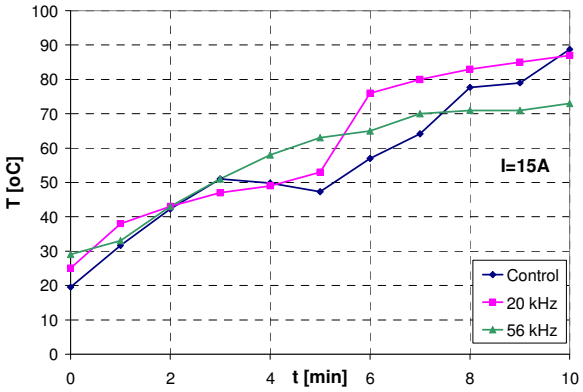
Table 1

I	10 A			15 A		
Probe	Con-trol	20 kHz	56 kHz	Con-trol	20 kHz	56 kHz
M [g]	1,946	1,972	2,014	3,014	3,064	3,096
MP [g/min]	0,194	0,197	0,201	0,301	0,306	0,309

From the Table 1, it can be observed a slight increase of mass transfer, especially at the higher working frequency. The most influent parameter on the mass-removal remains the working current, according to Faraday's law. However, the ultrasonic field can contribute to a most serious increase of mass-transfer. Unfortunately, the limitations of the laboratory equipment have not allowed to work with heavier pieces and higher currents, in order to obtain more spectacular results.



a). I=10A



b). I=15A

Fig. 6. The electrolyte temperature during the ECM process.

5. Conclusions

The main conclusions that can be inferred from the above experimental investigations, are:

- ECM process can be substantially assisted by the ultrasonic intensification field, especially in order to depassivate the workpiece surface during the machining;
- The ultrasonic frequency has a real influence on the perfomance of EMC process; a greater ultrasonic frequency results in a greater working current, and thus a higher mass-removal rate;
- Future efforts of our team will be oriented to up-grade the experimental set-up and to explore more ultrasonic frequencies at the same ultrasonic power level, different ultrasonic power levels at the same ultrasonic frequency, and different inter-electrode gaps, in order to have a more complex and accurate insight of the influence of the ultrasonic

intensification field in assistance of a specific ECM process.

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