

SHORT CONSIDERATIONS ON THE ULTRASONIC ACTIVATION OF THE ELECTRODE USED IN THE EDM/WEDM PROCESS

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ABSTRACT: The paper presents some considerations on the ultrasonic energy overlapping mechanism over the sparks energy at EDM/WEDM processing. In this respect, the ultrasounds effect on the dielectric environment of the gap is studied. In the dielectric environment, ultrasonic energy causes homogenization, dispersion, impact with the workpiece surface and evacuation of the eroded particles, respectively the occurrence of cavitation phenomenon. Depending on frequency and the vibration amplitude of the tool-electrode as well the dielectric liquid rigidity, the erosive capacity/erosion speed, dimensional accuracy and surface quality were determined by experiment, measuring the depth of machining, tool wear, machining speed, gap size and the surface roughness.
KEYWORDS: EDM/WEDM processing, ultrasonic energy, ultrasonic cavitation, dielectric rigidity, erosive capacity, roughness

1. INTRODUCTION

Electrical Discharge Machining (EDM), also known as spark machining, spark eroding, burning, die sinking, wire burning or wire erosion, is a manufacturing process whereby a desired shape is obtained by using electrical discharges (sparks). But EDM with an electrode ultrasonic activated is a very complex technological process. Concept of a viable mechanism for EDM into ultrasonic field is based on the logical interconnection of some known phenomena, experienced and applied by various researchers, resulting in overlapping effects and adjacent processes accompanying an electrical discharge in pulse. Aiming the ultrasonic energy influence on each stage that characterizes the electro-erosion process, has been found an overall improvement of the technological and machinability characteristics [1-4].

But in elementary workspace a multitude of electrical discharges accompanied by physic-chemical processes that is combine and influence each other happens. Not all voltage pulses applied in the workspace are accompanied by elementary processes of erosion. Some pulses have characteristics that deviate from normal ones and ultrasounds can generate side effects that alter the disruptive conditions. Both in the literature and in the patents [5-12] it was confirmed that the ultrasonic activation of the tool-electrode used in EDM leads, under certain conditions, to increase the erosion capacity, dimensional accuracy, shape deviations or reciprocal position, as well as the surface quality resulting from machining. All these parameters are important in the construction of machines and tools.

Overlapping of the ultrasonic energy over sparks energy that is initiate and manifests on the workpiece surface due to the pulse electric discharges, causes appearance of some phenomena physic - chemical complex in the technological interstitium (gap). The mechanism of material removal from workpiece and wear of tool-electrode is not wholly clarified [2, 7, 13-18]. Ultrasonic activation of the tool-electrode, explains the presumptive improvement of the electro-erosive process performances in the following way:

- increases the productivity of the erosion process by optimizing the conditions for initiation and development of pulse electrical discharges, the intensification of overlapping field effects over forced evacuation of eroded particles and refreshing the dielectric liquid [9, 10, 18-20] in conjunction with erosive action due exclusively to ultrasonic energy [3, 9 and 10];
- increases the dimensional and shape accuracy since the tool-electrode oscillates with a constant vibration amplitude relative to the equivalent surface of workpiece and has a sufficiently high energy to annihilate the effects of the electromagnetic field due to pulse electric discharge [21-28]; at the same time, a constant resistivity/conductivity of the dielectric liquid in the gap is ensure, to which is added the dispersion property of the eroded found particles in ultrasonic field;
- improves the workpiece surface quality because the eroded particles, that are into ultrasonic field, before being dispersed, act as some abrasive tools that by impact smoothes the surface resulting with micro-craters due to the pulsed electrical discharges [4, 12, 29-31].

2. ULTRASONIC ACTIVATION OF THE DIELECTRIC LIQUID FROM GAP

2.1 Acceleration and impact of eroded particles with the workpiece surface

The impact of free particles from workspace has a share in the total ultrasonic erosion capacity of about 20%. Higher values are obtained with larger size particles [3, 18-20, 32-35]. The eroded particles in the workpiece a dynamic impulse receive from the tool-electrode and are accelerated in the gap. These hitting the workpiece surface, being transmitted indirect dynamic shocks from the tool-electrode.

Diagram of the ultrasonic erosion of the workpiece surface by acceleration and impact of the particles removed from the piece is illustrated in Figure 1.

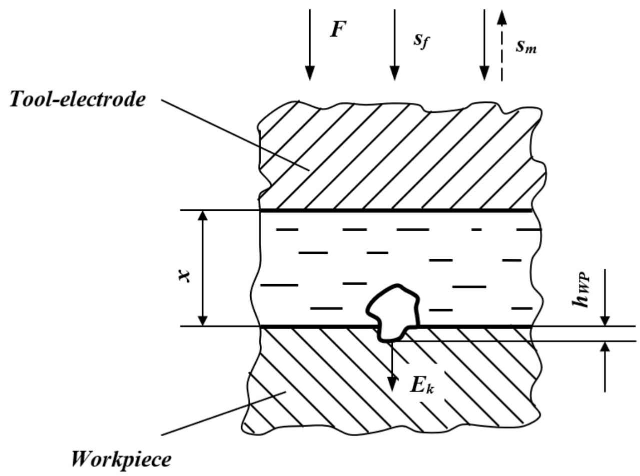

Figure 1. Acceleration and impact of eroded particles in the workspace
F - static force acting on eroded particles; E_k - the kinetic energy whom the eroded particle receives; h_{WP} - the penetration depth of the eroded particle into the workpiece; x - distance between electrodes at a time; s_f – feed speed of the tool-electrode; s_m - machining speed

According to the model developed by Markov, Show and Rosenberg [32, 36-38], the kinetic energy that an eroded particle receives is calculated with relationship:

$$E_k = \frac{\pi^3}{12} \frac{\gamma}{g} \xi^2 f^2 d^3 \quad (1)$$

where: γ - the specific weight of the eroded particles; g - gravity acceleration; ξ - the vibration amplitude of the tool-electrode; f - vibration frequency to resonance for the tool-electrode; d - the sphere diameter comprising an eroded particle.

As a result of the impact with the workpiece surface, the eroded particle penetrates the piece with a h_{OP} depth, overcoming the resistance imposed by the static force F:

$$F = \sigma_m S = \pi \sigma_m d h_{WP} \quad (2)$$

where: σ_m - mean strength for the workpiece deformation; S - the footprint projection of eroded particle on the workpiece surface ($S = \pi d h_{WP}$)

Calculating the mechanical work done by an eroded particle at the maxim force F_{max}:

$$L = \frac{1}{2} \pi \sigma_m d h_{WP}, \quad (3)$$

from the equality of relations (1) and (2), the penetration depth of the eroded particle into the workpiece can be determined:

$$Lh_{WP} = \pi \xi f d \sqrt{\frac{\gamma}{6\sigma_m g}} \quad (4)$$

According to the simplifying hypotheses deduced and developed by Kazanţev and Rosenberg [34], the quantity of material removed from the workpiece by each eroded particle is proportional to the third power of the eroded particle footprint diameter on the workpiece surface. Also, the number of shocks transmitted to the workpiece surface is inversely proportional to the second power of the eroded particle footprint diameter. In this way, we can calculate the amount of material removed off the workpiece surface in the unit of time, with relationship:

$$V_u = P_1 P_2 P_3 \sqrt{f^5} d \sqrt{\left(\frac{\pi^2 \xi^2 \gamma}{6\sigma_m g}\right)^3} \quad (5)$$

where: P_1 - correction factor taking into account the machinability coefficient of the piece; P_2 - correction factor taking into account the concentration of eroded particles in suspension (viscosity); P_3 - a correction factor that takes into account the effect of cavitation and the accompanying chemical phenomena.

2.2 Cavitational erosion of the dielectric liquid

Cavitational erosion phenomenon is due to the energy introduced into a liquid under the oscillatory action of a tool-electrode with ultrasonic frequency. Ultrasonic cavitation is a phenomenon of breaking and immediate restoring of a liquid under the influence of some hydraulic stresses sufficiently high or as a result of rapid and sudden some variations in pressure.

Cavitation phenomenon is related to the fact that liquid environments, although slightly transmit very large compressions in different directions, are extremely sensitive to relaxation efforts. When the ultrasound wave propagates in a liquid with the phase corresponding to a relaxation [39-44], then the liquid "breaks" and a very large number of tiny bubbles of air forms in it. Typically, these bubbles of air appear and propagate in areas where the resistance of the liquid was lower. These areas are those where there are already small bubbles of gas or particles of impurities, the liquid medium being non-homogeneous. The tiny cavities that appear, also called cavitation bubbles, are absorbed by the liquid mass after a very short duration.

In the approach phases of the electrodes, compression efforts of the liquid are produced. In this phase, cavitation bubbles are destroyed by implosion, producing powerful hydraulic shocks and local pressures exceeding 10^6 bar easily. Under the action of hydraulic shock waves, different from mechanical shock waves, the liquid penetrates into the fine network of micro-cracks previously created on the workpiece surface by the eroded particles. In the micro-cracks network on the workpiece fragile surface, the penetrated liquid has a dynamic effect as a mechanical wedge, leading to the detachment of material under particles form.

The cavitation bubbles due to ultrasound action, increase itself their volume several times [35, 41, 43, 45-47]. They are filled with the air or vapors resulting by evaporation during the breakdown dielectric liquid process. The volume reached by the cavitation bubbles and the pressure they develop depends on the duration, amplitude and the ultrasound frequency. In the immediate next phase sudden compression and rapid destruction of cavitation bubbles occurs.

However, this mechanism is a violent process [41, 43], during which pressures and high temperatures, emissions of chemicals, as well electric and electrochemical phenomena occur. When the implosion of cavitation bubbles take place, it is noted a substantial increase in temperature, reaching values up to 10^4 ^{0}K. Popoviciu [47] identified two mechanisms for increasing the temperature and pressure during the cavitation bubble implosion:

- by compressing the gases contained in the cavitational bubble, 10^6 bar implosion pressures are achieved, accompanied by a concomitant increase in temperature;
- by transforming the mechanical work in the heat - about 85% - resulted from the implosion.

After Inoue [9], the temperature can be calculated with a relation of the form:

$$T = K \sqrt[3]{\left(\frac{Z\, ln\lambda}{\rho}\right)^2} \tag{6}$$

where: Z - the number of ions; λ-collision coefficient of the dielectric liquid particles; ρ - the resistivity of the dielectric liquid in the discharge channel; K – Boltzmann’s constant ($1.38x10^{23}$ J/K)

According to the same author, the pressure can be determined with a good approximation by the relation:

$$P = (n_e - n_i)\, K\, T \tag{7}$$

where: n_e, n_i - the number of electrons, respectively the ions per volume unit; K - Boltzmann's constant; T - absolute temperature

At the same time, a potential difference [45, 47] appears between the walls of the cavity bubble. This is due to the fact that the ions in the liquid layer where the breakage occurs are routed according to the electric charge towards the opposite sides of the bubble. In this way, the cavitation bubble can be considered a capacitor. The intensity of the electric field is in this case, after Kurr and Obaciu [48]:

$$E = 4\,\pi\,\varepsilon \sqrt{\frac{\delta\, N}{S}} \tag{8}$$

where: δ - the cavitational bubble' diameter; N - the number of molecules dissociated in the volume unit; ε - the electrical charge of the monovalent ion; S - the section surface of the cavitation bubble.

3. INFLUENCE OF THE ULTRASOUND ON THE EDM/WEDM PROCESS

Oscillatory motion of the tool-electrode with ultrasonic frequency provides the sequence of electric discharge in pulse even in the limit state when g_{min} = *0*, since the mean value of the gap g is greater than zero. The experimental researches undertaken by Miţkevici [49] and recently by Jun et. al. [50], led to the highlight of three effects due to ultrasonic activation of the electrode:

- intensification of the EDM process due to redistribution the electrical discharges after energy;
- increase the breakdown distance and, implicity, the sparking gap, which has led to improved evacuation of the erosion products from the workspace; this effect is more strongly highlighted at low energies and small hydrodynamic forces occurring during pulsed electrical discharge;
- improving the material evacuation in the liquid phase from the workpiece crater.

Highlighting the performance of industrial equipment has taken into account technology and working practice in the industrial sector. For this reason a few hypotheses were accepted which were subsequently confirmed by experimental results [45]:

- between the electrical power consumed by the ultrasonic generator and the power delivered to the electroacoustic converter (mechanical assembly made up of a transducer, waveguide and tool-electrode), a linear dependence there is;

- the vibration amplitude of the tool-electrode is directly proportional to the power consumed/supplied by the ultrasonic generator;
- the minimum level of electrical power consumed/supplied by the ultrasound generator from which the tool-electrode vibrations are perceive, corresponds to a piezoceramic transducer vibration amplitude of 10-3 mm [35];
- the vibration amplitude of the electroacoustic converter is entirely transmitted to the tool-electrode.

Figure 2 shows the dependence of the material amount M removed from the workpiece depending on the vibration frequency of the tool-electrode.

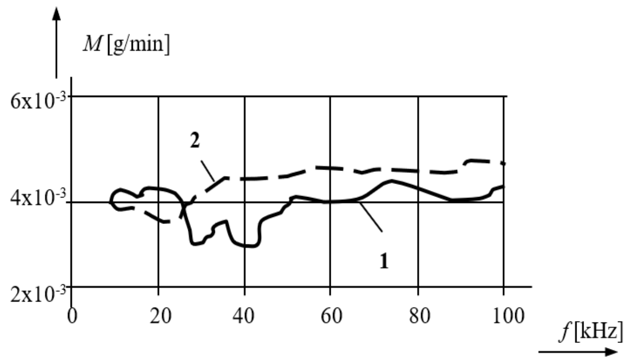

Figure 2. The erosive capacity M depending on the vibration frequency of the tool-electrode
M - material quantity removed from the workpiece; *f* - vibration frequency of the tool-electrode; *1* - minimum interstitium is $g_{min} = 0,3 \ x \ g_0$; *2* - minimum interstitium is $g_{min} = 0,5 \ x \ g_0$

A *RC* electro-erosive pulses generator was used under the following technological conditions: voltage pulse duration $RC= 10^{-5}$ s, idle voltage $U_0 = 100$ V, initial gap $g_0 = 0.040$ mm, and the tool-electrode vibration amplitude $\xi = 0.010$ mm. The erosive capacity *M* variation curve depending on the tool-electrode frequency is illustrated in two distinct positions determined by the minimum gap size: curve 1 has $g_{min} = 0.3xg_0$ and curve 2 has $g_{min} = 0.5xg_0$.

It can be noticed that large variations in erosive capacity occur in the range of *10 ... 40* kHz frequencies. For this reason, it is necessary adjustment and concordance the parameters of the electro-erosive pulses generator with the ultrasonic vibrations frequency of the tool-electrode. For example, Miţkevici's experimental researches [49] at $f = 23.5$ kHz and vibration amplitudes $\xi = 0.001$ mm led to the following results depending on the load capacity of the capacitor *C* from electro-erosive pulses generator: increased erosion capacity *M* relative to the electroerosive process without ultrasound, with 10% at $C = 2$ µF, 50 ... 80% at $C = 0.5$ µF and 55 ... 185% at $C = 0.2$ µF.

However, the role of ultrasonic vibrations on the tool-electrode is complex, influencing all the processing phases, from the breakdown of dielectric liquid up to the unfolding intimate phenomena for removing the particles from workpiece.

When machining workpieces of alloy steel A2 type SKD-10, DIN 1.2363 having a thickness $G = 10$ mm, Inoue [9] used a wire-electrode made of brass having diameter $\Phi_d = 0.2$ mm. A dielectric liquid of a certain distilled water type with a resistivity of $5x10^4$ Ω cm was used. The electrical pulses applied to the tool-electrode had a peak intensity of *30* A, pulse duration $t_i = 10$ µs and a pause time between pulses $t_p = 20$ µs. In the Wire-Cut EDM (WEDM) process without ultrasonic activation of the wire-electrode, an erosion speed of $s_e = 1.2$ mm/min was obtained. If the wire-electrode is ultrasonic actived at a frequency of *30* kHz, the erosion rate reaches *2.3* mm/min at a vibration amplitude of *0.001* mm and *2.0* mm/min at *0.003* mm amplitude, respectively.

The variation in mechanical stress of the wire-electrode has an insignificant influence on the erosion speed s_e. Thus, at a mechanical stress in the wire-electrode equivalent to a mass of *600* g and a variation range of ± (*5 - 300*) g, the erosion speed is practically constant in the frequency range of *1 - 50* kHz. For example, at *1* kHz, Inoue obtained an erosion speed $s_e = 1.9$ mm/min and at *3* kHz the erosion rate reached *2.0* mm/min.

Developing the experimental researches in the processing of some alloy steel SKD-10 of $G = 10$ mm thickness with a wire-electrode having the diameter $\Phi_d = 0.2$ mm, Inoue programmed the electro-erosive pulses generator with the following parameters: $t_i = 5$ µs, $t_p = 20$ µs and a peak current intensity of *27* A. The variation of the technological regime parameters - gap *g*, the depth of machining D_m, the surface roughness R_{max}, the relative wear of the wire-electrode W_r and the erosion speed s_e - according to the dielectric liquid resistivity R_d are illustrated in the diagrams of Figure 3.

It is noted that the gap size g changes in an inverse ratio proportional to the dielectric resistivity having an approximately linear variation curve. At values 10^6 - 10^7 Ω cm of the resistivity of the dielectric fluid, such as the distilled water, the gap is *0.010 ... 0.020* mm. At lower dielectric resistivity values of about 10^2 - 10^4 Ω cm, the gap can reach values of *0.040 ... 0.050* mm.

The erosion speed s_e sudden increases when the dielectric resistivity slightly exceeds the value $5x10^4$ Ω cm, while the relative wear of the filiform electrode W_r decreases considerably between 10^4 Ω cm and $5x10^5$ Ωcm. Thus, if the relative wear W_r is about 80% when the dielectric fluid resistivity higher than 10^6 Ω cm, it decreases to 20% for a resistivity of 10^2 Ω cm.

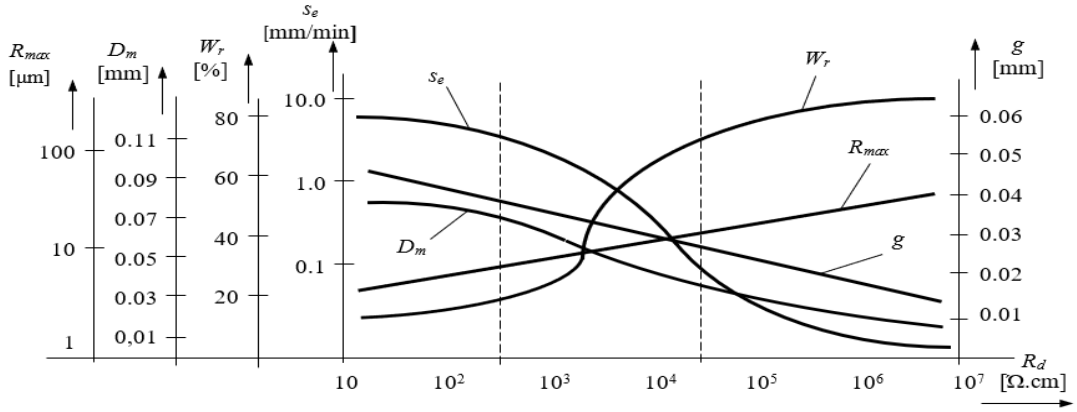

Figure 3. The variation of the technological parameters according to the dielectric liquid resistivity
R_{max} -the maximum roughness obtained on the workpiece surface; D_m - the depth of machining; W_r - the relative wear of the wire-electrode; s_e - the erosion speed; g - gap; R_d - the resistivity of the dielectric liquid

The machining depth D_m varies descending with dielectric resistivity. Higher processing depths are obtained in the range of 10^2 - $5x10^2$ Ω cm. Also, the surface quality expressed by R_{max} parameter is in an approximately linear dependence with dielectric resistivity. Lower roughness to lower resistivity values are obtained.

From analysis of these technological features, results that the acceptable parameters for a working regime can be obtained, when working with a dielectric liquid - commonly, deionized domestic water - having a resistivity in the range of $5x10^2$ - $5x10^4$ Ω cm. In Figure 3, this range is marked by the broken line. Above $5x10^4$ Ω cm, the erosion speed s_e decreases very much. In this situation, the influence of ultrasound energy on the productivity of the WEDM process is insignificant. On the other hand, at lower dielectric resistivity values below $5x10^2$ Ω cm, the machining depth D_m increases considerably, which leads a decrease in machining accuracy.

If for various reasons dielectric liquid does not circulates forcefully through the gap, its resistivity considerably over time is dimishes. In the graph illustrated in Figure 4, Inoue [9] represented the mode of variation of the dielectric fluid resistivity in time starting from an initial value of $5x10^4$ Ω cm.

It can be seen that within a few minutes, the resistivity of the dielectric fluid Rd may decrease several times. This negatively influences the operating parameters of the technological process. The explanation of this phenomenon lies is increase the temperature of the dielectric liquid due to the energy emitted from the pulse electric discharges. Increasing the temperature of the dielectric liquid favors the increase of the carbon dioxide dissolution capacity in water and, implicitly, its concentration in water. Consequently, the dielectric fluid resistivity decreases. For this reason, sometimes the forcefully circulation of the dielectric liquid through gap along the processing area is required.

Generally, vibration of the ultrasonic frequency electrode contributes decisively to the intensification of the EDM processes. Positive results were obtained when the electrode was activated ultrasonically with amplitudes $(1 - 50) \times 10^{-3}$ mm, usually $(1 - 5) \times 10^{-3}$ mm, and at frequencies of *10 - 50 (100)* kHz [11, 45].

Experimental researches at the 40 kHz frequency by activating the wire-electrode in two-points after two rectangular directions in space revealed the influence of the operating parameters on the pre-established technological parameters [35].

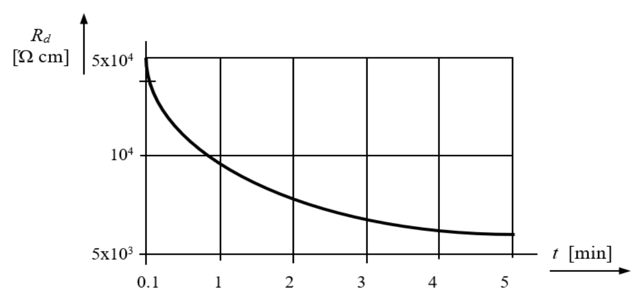

Figure 4. Variation of the dielectric liquid resistivity in time
R_d - resistivity of the dielectric liquid; t - time

More workpieces made of a high steel type W 1.2379 (X 155 CrVMo 12 1) having a thickness $G = 40$ *mm* were machined. A wire-electrode with a diameter of $\Phi_d = 0.2$ *mm* and a dielectric liquid (domestic water) with a resistivity of $5x10^4$ Ω cm was used. The dielectric breakdown current intennsity was *8.7* A, pulse duration $t_i = 10$ µs and pause time between pulses $t_p = 20$ µs.

Thus, the diagram of Figure 5 shows the vibration amplitude influence supplied the electroacoustic converter (mechanical assembly made up of the transducer and the waveguide, possibly mechanical adaptation elements specified to the technological application) depending on the variation in the electrical power provided by the ultrasound generator.

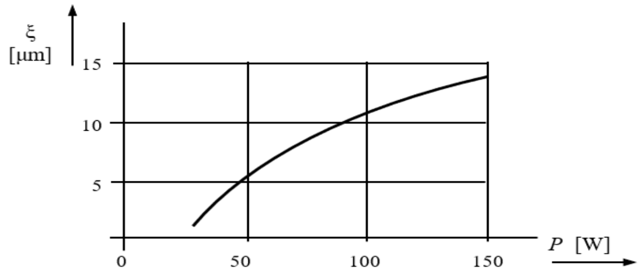

Figure 5. Variation the vibration amplitude of the electroacustic converter according to the ultrasonic generator power
ξ - vibration amplitude of the electroacoustic converter;
P - power of the ultrasound generator

It can be seen that for relatively low amplitudes around *(1 - 3)x10-3* mm, the power of the ultrasonic generator is about *20 - 30* W. This finding is of great importance in the energy computing for the electroacoustic converter-ultrasound generator assembly, facilitating their miniaturization and their implementation in the mechanical structure of the EDM technological equipment and CNC control equipment of the EDM numerical machine.

By maintaining constant the vibration amplitude of the tool-electrode by changing controlled of the waveguide with different k_A amplification factor values, in Figure 6 is shown its variation according to the W_{sp} energy density through the gap.

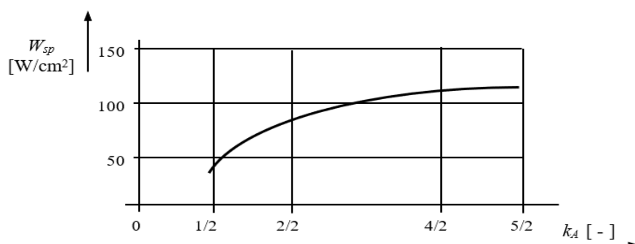

Figure 6. Variation of the energy density through gap according to the amplification factor
W_{sp} - energy density through gap; k_A - amplification ratio of the waveguide

In the case where relatively large thickness workpieces are processed by EDM with wire-electrode, higher energy densities are required. In this case, the electroacoustic converter is correlate with the type of electro-erosive pulse generator. Thus, the electroacoustic converter can be simple and easily adapted to the technological necessities by changing the waveguide with one that ensures a higher k_A amplification factor.

The ultrasonic activation of the wire-electrode in two points after two rectangular directions in space necessitates constructive restrictions. Thus, it is difficult and uneconomical to achieve and control the operation of several identical electroacoustic converters. Typically, they are designed and dimensioned strictly on the transducer frequency for the mechanical assembly to operate at resonance. At resonance, the electroacoustic efficiency is maxim.

Practically, the physical realization of ultrasound transducers covers a relatively wide spectrum of frequencies and amplitudes. From the point of view of the industrial application, the real case of the ultrasound efficiency on the EDM/WEDM process is interesting when there are functional differences between the electroacoustic converters.

Figure 7 shows the influence of punctual frequency differences on the productivity of WEDM process when the wire-electrode is activated ultrasonically in two points after two rectangular directions in space. Frequency variation range is 1 kHz, ranging from 39.5 kHz to 40.5 kHz.

From spatial composition of the two oscillatory movements resulted in a component for which the difference between the working frequencies was 0.27 kHz and resulted in a peak machining productivity of about 130 mm^2/min. It should be noted that for values of less than 0.2 kHz of the differences between the primary frequencies of the guide elements of the ultrasonically activated wire-electrode, a more pronounced decrease in processing productivity is obtained. At values greater than 0.3 kHz, the processing productivity tends to stabilize at 30 - 35 mm^2/min.

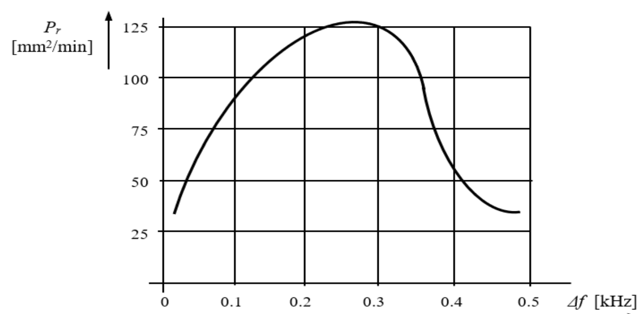

Figure 7. Variation the processing productivity according to the frequencies difference of the wire electrode vibrated in two points after two rectangular directions in space
P_r - the processing productivity; Δf - the range of the frequencies variation

4. RESULTS AND DISCUSSIONS

Measurement results confirm the Kurr, Obaciu and Wertheim models with great precision. The removal of material takes place in the first microseconds under the action of electrodynamic forces and by evaporation. At the end of the electric discharge period, material is supplementary removed due to the boiling that take place as a result of the pressure drop in the gas bubble surrounding the plasma column. Any phenomenon that leads to lower current density in the gap causes a decrease of the erosive capacity

[7, 17, 44, 51 and 52]. On the other hand, the use of trapezoidal current pulses can be convenient for protecting the tool-electrode.

In case of EDM/WEDM processing without ultrasonic activation of the tool-electrode, the energy crater magnitude depends mainly on the shape, pulse duration, the share from discharge energy received by the workpiece and its erosion resistance. The discharge energy We are determined by the time function of the voltage u(t) and current i(t) during the discharge and is calculated with the relation:

$$W_e = \int_0^{t_i} u(t)\, i(t)\, dt \qquad (9)$$

At a constant value of the energy pulse, the erosion crater volume Vi depends on the pulse duration ti and the connection polarity of the electrodes [49, 51]. Figure 8 shows the variation of the erosion crater volume Vi of the electrodes according to the voltage pulse duration.

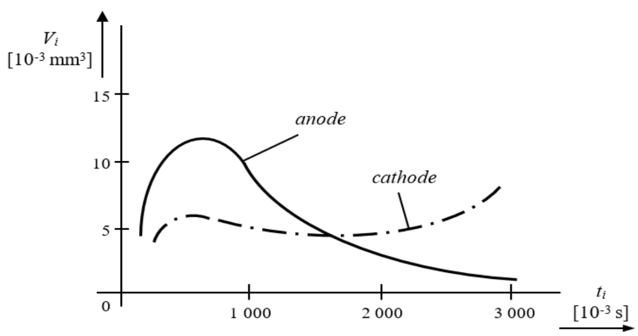

Figure 8. Variation of the erosion crater volume of the electrodes according to the voltage pulse duration
V_i - the erosion crater volume; t_i- the voltage pulse time

If the voltage and the amplitude of the electric current are constant [7, 49 and 51], then the erosion crater volume also depends on the polarity and increases with the increase in the duration of the voltage impulse t_i. Figure 9 illustrates the variation of the erosion crater volume on the workpiece surface according to the pulse duration at voltage and constant current.

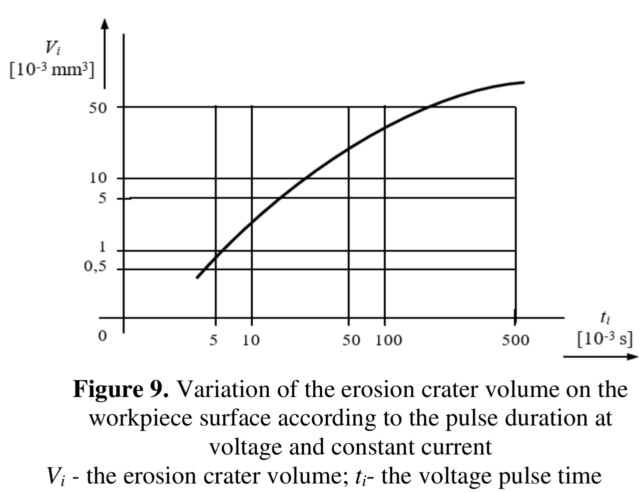

Figure 9. Variation of the erosion crater volume on the workpiece surface according to the pulse duration at voltage and constant current
V_i - the erosion crater volume; t_i- the voltage pulse time

The ultrasonic energy input into the workspace influences the technological parameters specific to the EDM/WEDM process mainly by initiating and maintaining the cavitation effect in the dielectric liquid. Experiments have shown that by the movement of the small cavitation bubbles having R0 radius between them act, either attraction forces or rejection forces [45, 47].

By attraction, bubbles merge and form larger bubbles. Their implosion creates a shock wave with a maximum pressure given by the relationship [47]:

$$P_{max} = \frac{P_0}{\sqrt[2]{256}} \left(\frac{R_m}{R}\right)^3 \qquad (10)$$

where: P_0 - the hydrostatic pressure of bubble having R_0 radius; R_m - the cavitational bubble radius before compression; R - the compressed bubble radius.

Cavitational bubbles continuously increase their volume under the action of the ultrasonic field. Under the influence of ultrasound they begin to pulse having a harmonic oscillatory motion and the corresponding resonance frequency f0 can be calculated with relation [47]:

$$f_0 = \frac{1}{2\pi\, R_0} \sqrt{\frac{3\chi}{\rho} \left(P + \frac{2\sigma}{R_0}\right)} \qquad (11)$$

where: χ - the ratio of the specific heat corresponding to the existing gas inside the cavitation bubble; ρ - density of the dielectric liquid; P - hydrostatics pressure; σ - the surface tension of the dielectric liquid.

It is noted that if the frequency of the ultrasound is less than the resonance frequency, the cavitational bubbles are in an unstable state. In this case, the dilation and their implosion effect are reduced. However, if the frequency of ultrasound is higher than the resonance frequency, the bubble implosion are no longer produced, and they acquire a complex oscillatory motion. In this case, the volume of cavitational bubbles increases continuously, constituting the main mechanism for releasing a liquid under the action of the ultrasonic field. Therefore, in order to ensure the initiation and development of cavitation bubbles in the dielectric liquid in the gap between electrodes, the ultrasonic oscillation frequency of the tool-electrode is required to be equal or superior to the cavitation bubble resonance frequency.

Secondary effects of homogenization and dispersion of eroded particles in the ultrasonic field lead to their rapid evacuation from the gap. On the other hand, ultrasonic oscillations of the tool-electrode cause acceleration of the eroded particles. Some of these strikes the workpiece surface before being evacuated, and another part reaches to be fixes on the tool-electrode surface by impact.

The machinability coefficient of the materials can be calculated with the relation [40]:

$$K_{pr} = \frac{\tau_r}{\sigma_r} = \frac{R_f}{R_m} \quad (12)$$

where: τ_r, R_f - tangential mechanical tension at tensile or shear breaking; σ_r, R_m - normal mechanical tension at tensile or shear breaking.

For tool-electrodes made of copper or copper alloys (brass), the value of the machinability coefficient is $K_{pr} < 1$. It is deduced that eroded particles in the gap are embedded in the tool-electrode. If the electrode is filiform, then by the relative displacement motion along its axis with a certain speed, the eroded particles from gap are also evacuated.

5. CONCLUSIONS

Ultrasonic activation of the tool- electrode used to the EDM/WEDM process, leds to the occurrence of some complementary phenomena for initiation and development of a pulsed electrical discharge, such as:

- The easier appearence of the gaseous phase;
- Shortening the random time for electrical discharge preparation;
- Faster deionization of the workspace and restoration of its dielectric rigidity;
- Removal of new particles from the surface subjected to processing by additional local energy activation of the surface layer;
- Removal of new particles from the surface subjected to processing by increasing the intensity of the forces leading to the expulsion of the activated material;
- Removal of new particles by cavitational abrasion;
- Rapid evacuation of eroded particles from the workspace which are transported both by the dielectric liquid as well by the wire-electrode in the case of WEDM process.

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