# STUDY ON WIRE ELECTRICAL DISCHARGE MACHINING (WEDM) PROCESS UNDER THE CONDITIONS OF ULTRASONIC ACTIVATION OF THE DIELECTRIC FLUID

Viorel-Mihai Nani[1], Dumitru Mnerie[2], Alin Nani[3]

[1] „Politehnica" University Timisoara, Research Institute for Renewable Energy, G. Muzicescu Street, no. 138, Timisoara, Romania 300774, E-mail: viorel.nani@upt.ro

[2] „Politehnica" University Timisoara, Mechanical Faculty, Mihai Viteazu Blv., no 1, România, E-mail: dumitru.mnerie@upt.ro

[3] „Politehnica" University Timisoara, Mechanical Faculty, Mihai Viteazu Blv., no 1, România, E-mail: alin.nani@student.upt.ro

ABSTRACT. In this paper, few mechanisms for removing material by Wire Electrical Discharge Machining (WEDM), with ultrasonic activated wire electrode are analyzed. Vibrations with an ultrasonic frequency of the wire electrode to the dielectric fluid from gap have been transmitted, influencing the performances of the WEDM process. The study is focuses on the phenomena that occur in dielectric fluid, as: the priming of the electrical discharge, the electrical discharge evolution, and the physic-chemical effects into the gap, as well the material removal. We found that the ultrasonic energy transferred to the dielectric fluid from the gap intensifies the electro-erosive phenomena, beginning with the emergence of the gaseous phase and the initiation of the discharge channel, and ending with the evacuation of erosion particles.

KEYWORDS: wire electrode ultrasonic activated; WEDM process in ultrasonic field; material remove from the workpiece; ultrasonic cavitation bubbles

## 1. INTRODUCTION

The increasing use of the WEDM process in industry has led to a growing concern about the search for opportunities to improve conditions. The ultrasonic activation of the dielectric fluid represents one of the most interesting directions of the research, with good results. About this aspect, the specialized literature includes important results that confirm the deepening of the researches of the phenomena that took place in the work space. For the present research, some aspects of the movements of the empty bubble during a single electric discharge presented in a first report by Ikeda [1] were considered. Mironoff's remarks [2] on the thermal effects of erosive impulses were also noted. The Okada Coordinated Team [3] assessed the distribution of sparks and wire vibration in WEDM. Recent research by Kitamura and Kunieda [4] sheds light on EDM phenomena using transparent electrodes. The conclusions of Mitkevici's research [5] and Savii et al [6], respectively, on the influence of ultrasonic energy on each stage that characterizes the EDM process were also analyzed. There has been an overall improvement in technological features as

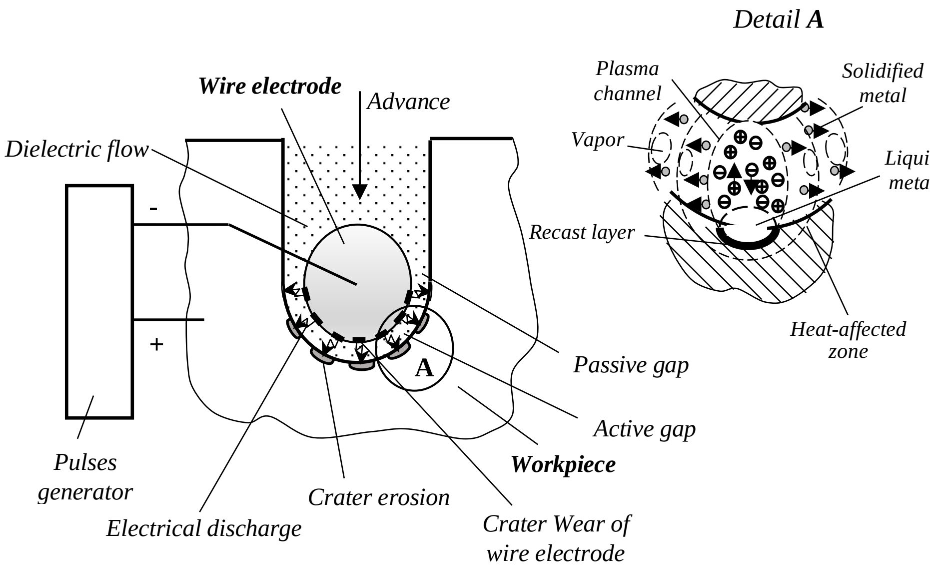

Figure 1 Schematic diagram of WEDM processing [7].

well as processability. A schematic diagram of WEDM processing is shown in Figure 1.

According to the migration theory of Bakuto [8], the material removed from workpiece m, for a singular electrical discharge is determined after Miţkevici [5] with relation:

$$m = \frac{V_c \cdot B}{S_0^2}\int_0^\tau I^2 dt \quad (1)$$

where: $V_c$ - is volume of material removed from the erosion crater made by a singular electric discharge in workpiece; $B$ - is correction factor that considers the nature and physical-mechanical properties of the wire electrode material; $S_0$ - is a surface projection of the erosion crater in the work plan, crater made by a singular electric discharge in workpiece; $I$ - is the dielectric breakdown current intensity; $\tau$ - is duration of the pulses electric discharge.

During a time of vibration of the wire electrode, the entire amount of material removed from the surface of the workpiece, can be expressed as the sum of the resulting products from the eroded material quantities $m_i$, for each singular electrical discharge $i$ and the wire electrode vibration frequency denoted $f$:

$$M = \sum_{i=1}^{n} m_i \cdot f \quad (2)$$

After theory of Okada et al [9], in the general case it can write:

$$\frac{V_0}{S_0^2}\int_0^\tau I^2 dt = \varphi(U_{ai}) \quad (3)$$

where: $U_{ai}$ – is the priming voltage corresponding to the electrical discharge $i$.

Then the relationship (1) becomes:

$$M = B.f\sum_{i=1}^{n} \varphi(U_{ai}) \quad (4)$$

Equation (4) can be solved only when $U_{ai}$ is known. But the priming voltage $U_{ai}$ can be determined from the dielectric breakdown conditions only, depending on the relative position of the wire electrode ultrasonic activated and workpiece. It is considered that between wire electrode and workpiece is a variable distance versus time.

## 2 TESTING PLANT

The experiments were performed on a test plant consisting of a WEDM machine with an ultrasonically activated wire electrode at two points located two directions perpendicular to space [7]. Two special devices were used to ultrasonically activate the wire electrode. They are mounted in the structure of the mechanism that drives the wire electrode, in the immediate vicinity of working area. One schematic drawing of the testing plant is present in Figure 2.

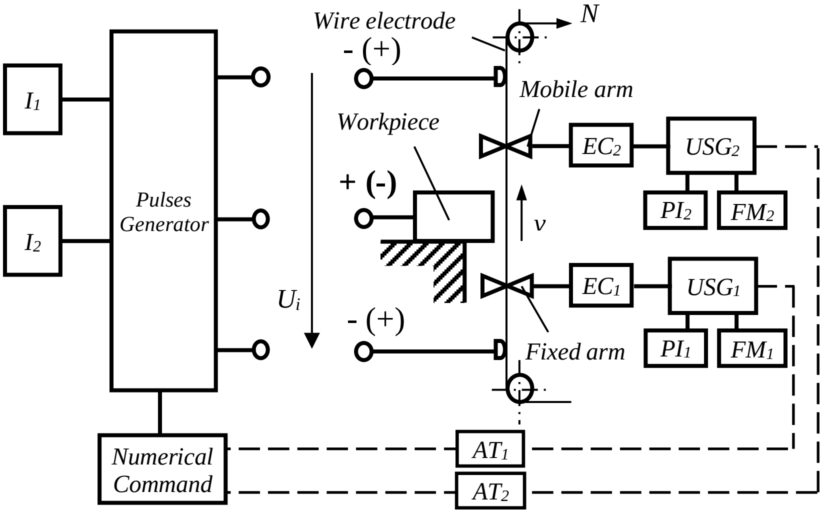

Figure 2 Schematic drawing of general principle of the testing plant

The testing plant is based on $USG_1$ the ultrasonic generator which transmits a high frequency signal toward the $EC_1$ electroacoustic converter mounted in the fixed arm. Another ultrasonic generator $USG_2$ is assembled with $EC_2$ in the mobile arm of WEDM machine. The electroacoustic converter $EC_{1,2}$ is a mechanical assembly that comprises: a piezoceramic transducer, an ultrasonic waveguide and a guiding element of the wire electrode (made in this construction by sapphire or diamond).

The energy for wire electrode is done by the Pulses Generator. The power supply of the ultrasonic generators connected to $EC_{1,2}$ is made individually for each USG, from the autotransformers $AT_{1,2}$, and of one power indicator $P_{1,2}$. During the process, the vibration frequency provided by each ultrasonic generator is continuously measured. All recorded values are displayed by a frequency monitor, $FM_{1,2}$. The current required to activate the dielectric liquid $I_{1,2}$ is produced by a Pulses Generator and the wire electrode follows the path, the workpiece's trajectory is controlled by a Numerical Command (CNC). The wire electrode it's moving is moving along the axis with $v$ speed and that is stretched by $N$ force.

## 3. STUDY OF THE PHENOMENA OCCURRING IN DIELECTRIC FLUID FROM GAP DURING AN EROSION ACT

The complexity of WEDM processing is well known. Moreover, in the case of ultrasonic activation of the wire electrode, the technological process increases in complexity, but brings advantages to the processing conditions. In order to design a viable WEDM processing mechanism, the logical interconnection of phenomena known, experienced and previously applied by various researchers was considered. There have been some overlapping effects and adjacent processes that accompany an electrical impulse discharge. Analyzing the influence of ultrasonic energy on each stage of the EDM process, a real general improvement of the technological characteristics of WEDM processing was observed. There were also some physico-chemical processes that combine and influence each other during electrical discharges. It should be noted that not all voltage pulses applied in a vacuum are accompanied by elementary erosion processes. Thus, some pulses deviate from the normal characteristics. Ultrasonic waves can cause certain side effects that change the conditions of electric discharges.

This confirms some findings from the literature, (for ex. [9-11]) about the fact that during the WEDM process the ultrasonic activation of the wire electrode in certain situations results in an improvement of the erosion capacity. Generally, most of research conducted in this area had highlighted only this technological parameter [13-17]. In view of the importance and other parameters which are decisive for the construction and operation of the processing machines, further clarification is required on dimensional accuracy, shape deviations, reciprocal position or surface roughness resulting from the processing. Also, the theoretical studies that were very well developed strictly in the WEDM processing domains or ultrasound, they failed to fully model a mechanism that would reflect all the processes that take place in the dielectric fluid in the workspace. A clearer explanation of the interference phenomena between pulsed electric energy and induced ultrasonic energy is needed. Therefore, it is appropriate to analyze more carefully the influence of specific factors on the processing in the presence of high-energy ultrasonic waves. Further research is needed, in particular on the methods of ultrasonic activation of the wire electrode, the composition and interference of the waves in the wire electrode, as well as the improved conditions due to the magnetic field resulting from the working environment. In the processing process, a complex of phenomena is manifested, so that the removal of the material from the workpiece is determined at different times, by forces of a thermal, mechanical, hydraulic, electrostatic, magnetic, aerodynamic, etc. nature. [12 and 21].

The explanation of how to remove the material with the help of strong electric fields, due to high current densities ($10^5$ ... $10^7$ A/cm$^2$), was given by Williams E.M., long before [18]. The detachment of metal particles from the crystal lattice of the metal material from which the workpiece is made, is favored by the mechanical stresses that form and which are applied on small surfaces, exceed the strength of the material. The material volume removed by an electric discharge $V_W$, can be calculated with formula:

$$V_W = \frac{0.44 \ x \ 10^{-6}}{\sigma_t} \frac{1}{\sqrt[3]{I_m}} t_e \qquad (5)$$

where: $\sigma_t$ – is tensile strength of workpiece; $I_m$ - is mean electric current of discharge; $t_e$ – is the discharge time.

Other additional analyzes were performed, such as his Kurr et al [19], that found some differences compared to the mathematical relation (5) for the case of various impulse durations.

Was developed by Loeb et al [20], another model assumes that all the energy in plasma column is transmitted to the electrodes. Considering the basic formula of general equation of heat transfer:

$$\Delta\theta = \frac{1}{a}\frac{\partial\theta}{\partial t} \qquad (6)$$

where: $a = \frac{\lambda}{\rho \ c}$ – represent an experimentally determined correction factor that is not assumed to be temperature dependent; $\lambda$ – means the thermal conductivity; $\rho$ - mass density; $c$ - specific heat.

The temperature in the axis passing through the center of the column section was determined using the relation used by Wertheim R el al [22]:

$$\theta(t) = \sqrt{\frac{c \ \rho}{4\pi\lambda}} \int_a^b x \ dx \int_0^\tau \theta(\tau)\sqrt{t-\tau} e^{\frac{h^2-x^2}{4a(t-\tau)}} dt \qquad (7)$$

where: $a$, $b$ - are the integration limits for the variable x; $h$ – means the crater depth; $\theta(t)$ - caloric flow rate per unit area and time.

So, according to the relationship (7), the volume of material removed from workpiece was practically verified with an accuracy of ± 10%. For these reasons, an order of metals has been established, according to their electro erosive capacity, as follows: tungsten, molybdenum, tantalum, copper, cadmium, steel, vanadium, aluminum and brass. From the first microseconds, the material is removed from the workspace, both under the action of electrodynamic forces and by vaporization. At the end of each period of each electric discharge, a boiling process occurs which favors the removal of the material. This is due to the pressure drop in the gas bubbles around the plasma column. It is estimated that any phenomenon that contributes to a decrease in current density causes a reduction in EDM capacity [23]. In another train of thoughts, for the protection of the wire electrode it is recommended to use trapezoidal current pulses.

In the classical conditions of use of WEDM, the size of the energy crater depends mainly on the shape and duration of the impulse, the share of the discharge energy received by the workpiece and its resistance to erosion. The discharge energy $W_e$ is determined by the pulse time $t_i$ of the electric current $i(t)$ and the voltage $u(t)$ in the period of the discharge. It is calculated using relationship:

$$W_e = \int_0^{t_i} u(t)\, i(t) dt \tag{8}$$

In Figure 3, is present the diagram of the erosion cavity volume $V_i$ of the electrodes in correlation with the variation of the voltage pulse time $t_i$.

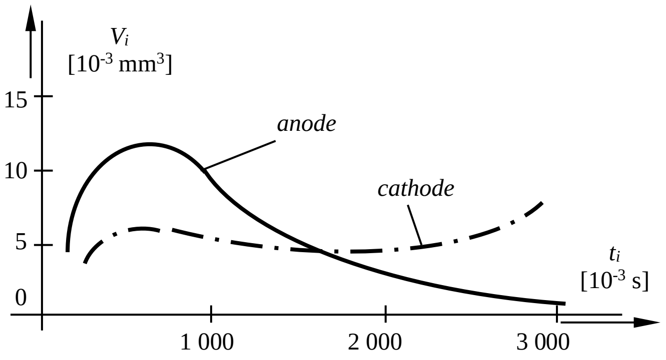

Figure 3 Diagram of the dependence of the electrode’s erosion cavity volume in according to the voltage pulse time

The specific technological parameters of WEDM are influenced by the ultrasonic energy that is introduced in the workspace, especially by initiating and maintaining the cavitation effect in the dielectric liquid. This experiment bring evidence on the movements of smaller cavitation bubbles with a radius of $R_0$, either attractive forces or repulsive forces act between them [24]. By this attraction, the bubbles merge and form larger bubbles. So, their implosion creates a shock wave with a maximum pressure given by:

$$P_{max} = \frac{P_0}{\sqrt[3]{256}} \left(\frac{R_m}{R}\right)^3 \tag{9}$$

where: $P_0$ – represent the hydrostatics pressure of the bubble with $R_0$ radius; $R_m$ – means the cavitation bubble radius before compression; $R$ – is compressed bubble radius.

Under the action of the created ultrasonic field, the cavitation bubbles continuously increase their volume. In this case, under the influence of ultrasound, they begin to pulsate with a harmonic oscillating motion, and the corresponding resonant frequency $f_0$ can be calculated using relation [24]:

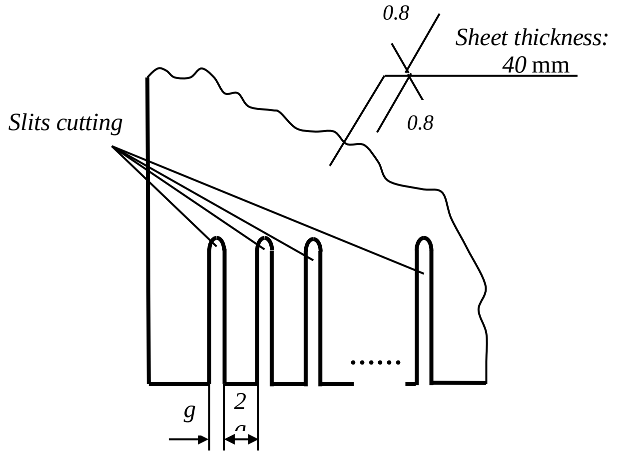

Figure 4 Preparation scheme of workpiece.

$$f_0 = \frac{1}{2\pi R_0} \sqrt{\frac{\chi^3}{\rho}\left(P + \frac{2\sigma}{R_0}\right)} \tag{10}$$

where: $\chi$ – means the specific heat ratio corresponding to the gas inside the cavitation bubble; $\rho$ – is the density of the dielectric liquid; $P$ – is the hydrostatic pressure; $\sigma$ – represent the surface voltage of the dielectric liquid.

It is noted that if the ultrasound frequency is lower than the resonance frequency, cavitation bubbles are in an unstable state. In this situation, their effect of the expansion and implosion is reduced.

It was found that if the ultrasound frequency is higher than the resonant frequency, then the bubbles will move in a complex oscillating motion, and the implosion no longer takes place. In this case, the bubbles volume increases continuously grows, the cavitation being the main mechanism of evacuation 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 from gap, it is necessary that the frequency of the ultrasonic vibration of the wire electrode be equal to or greater than the resonant frequency of the cavitation bubbles. Side effects of homogenizing and dispersing the eroded particles from ultrasonic field leads to their rapid evacuation from gap. On the other hand, eroded particles are accelerated due to the ultrasonic frequency oscillations induced in the wire electrode. These particles follow certain trajectories, both in the direction of the surface of the workpiece and towards the surface of the wire electrode. Due to the impact, some particles attach to these surfaces and others disperse into the workspace.

## 4. EXPERIMENTAL RESEARCH

The erosion capacity experiments measured by cutting speed $c_s$, were performed on samples were made from alloy steel sheets 34 MoCrNi 15, DIN 1.6582, with 40 mm - thickness and heat treated for hardness of 54-56 HRC. The surfaces were rectified to ensure a good condition for working and to allow precise adjustment of the wire electrode perpendicular to these surfaces [21].

The experimental research was based on the use of WEDM ultrasonic processing technology to cut slits at one end of the 4mm thick sheet metal piece, machined for 15 min.

The scheme of cutting the slits is shown in Figure 4. Lots of 5 slots cut with different technological processing regimes were made. The average arithmetic values of the measured dimensions of the five consecutive cut samples were retained. Table 1 shows the power values consumed by the ultrasonic generators in relation to the values of the set cutting speed.

Table 1

| *Parameter* | *Without ultrasonic activation of electrode* | *With ultrasonic activation, [W]* | | | |
|---|---|---|---|---|---|
| | | 10 | 20 | 30 | 40 |
| *Cutting speed,* $c_s$ *[mm/min]* | *0.378* | *0.635* | *0.664* | *0.673* | *0.663* |

A high-grade alloy steel material was used for the experiment, type X210 CrW 12 DIN 1.2436, commonly used in the manufacture of molds. After heat treatment, these steels usually provide hardness by 60 ... 62 HRC. For the research was used, 80 mm wide prisms were cut transversely, using the ultrasonically activated wire electrode. In a single pass, for each case, thicknesses were cut These prisms are cut transversely to a width of 80 mm, following a dimensional diagram shown in Figure 5. Table 2 shows the values of the cutting speeds for each case, as well as the recorded values of electrical current for dielectric breakdown I [A].

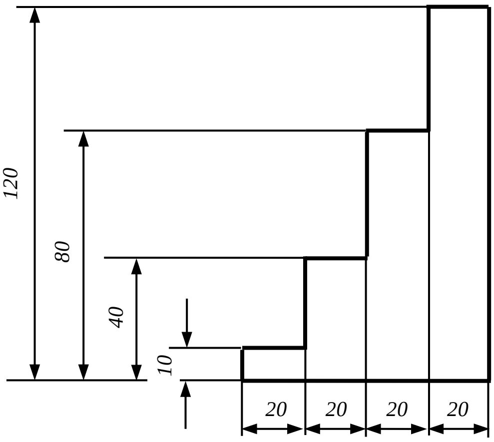

Figure 5 Top view of the sample in the form of stepped

Table 2

| *Parameter* | *The sample thickness, [mm]* | | | |
|---|---|---|---|---|
| | 10 | 40 | 80 | 120 |
| *Cutting speed* $c_s$ *[mm/min]* | *1.487* | *0.871* | *0.685* | *0.620* |
| *Electrical current for dielectric breakdown, I [A]* | *1.88* | *4.74* | *8.74* | *13.88* |

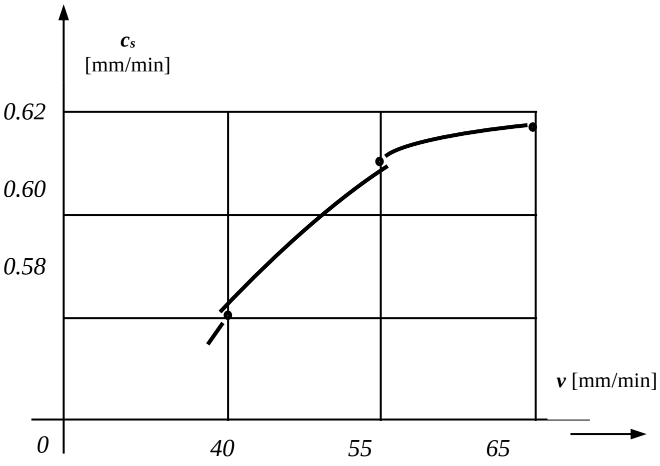

Figure 6 Graphic representation of the dependence of the cutting speed relative to the displacement speed of the wire electrode

Figure 6 shows the graph of the variation of the cutting speed $c_{S}$, as a function of the speed of movement $v$, characteristics of the wire electrode along its axis, for the case of cutting the sheet to a thickness of 120 mm. In order to determine the maximum performance that WEDM equipment can achieve, if the wire electrode is activated by ultrasound, the experiment was performed by varying the intensity of the electric current for dielectric breakage, gradually increasing the values to the limit of negative effects on processing. In this way it was observed that either the wire electrode breaks often or the technological process is blocked and can no longer continue due to the short circuit formed between the wire electrode and the workpiece. In the table 3 it can observe the correlation between the cutting speed ($c_s$) and the current intensity for the fault dielectric.

Table 3

| *Parameter* | *Processing method used* | *Electrical current for breakdown dielectric liquid, I [A]* | | | | |
|---|---|---|---|---|---|---|
| | | 1.88 | 2.22 | 2.90 | 3.28 | 4.42 |
| *Cutting speed, $c_s$ [mm/min]* | Without ultrasonic activation | *0.401* | *0.424* | *0.465* | *Wire electrode often breaks* | - |
| | By ultrasonic activation | *0.698* | *0.740* | *0.805* | *0.860* | *0.889* |

## 5. CONCLUSIONS

Following the experiments performed, it was found that uultrasonic activation of the wire electrode led to an increase in the cutting speed by WEDM. Regardless of the ultrasonic activation way of the wire electrode, in the advance direction or perpendicular to this direction, an increase in the cutting speed of about 25 ... 37% is usually obtained. This increase in cutting speed can reach, under certain conditions, even at 84-93% for the ultrasonic activation of the wire electrode at two points after two directions perpendicular in space.

Ultrasonic activation of the wire electrode increased the electric current intensity for breakdown dielectric to values that normally cannot be reached only by WEDM. In all the cases studied, the ultrasonic vibration of the wire electrode led to an increase in the electrical current intensity for breakdown dielectric by at least two steps.

From the study of the literature and from the investigation of the practice of using WEDM machines with wire electrode, there are no data on industrial implementation of ultrasonic activation of wire electrode, but there are results of other researchers, who create the premises for using the advantages of this technological intervention. It is considered necessary to redesign the machines with the introduction of the possibility of implementing the classic WEDM machines with suitable devices to increase performance; These include special devices for ultrasonic activation of the wire electrode. This paper adds further arguments in this regard.

## REFERENCES

[1] Ikeda M., (1972), *The movement of a bubble in the gap depending on the single electrical discharge, (first report)*, Journal of The Japan of Electrical Machining Engineers, 6 (11): 12-26

[2] Mironoff N.L., (1977), *Thermal effects of erosive pulses*, ISEM 5, Wolfsburg

[3] Okada A., Uno Y., Nakazawa M., Yamauchi T., (2010), *Evaluation of spark distribution and wire vibration in wire EDM by high-speed observation*, CIRP Annals, 59 (1), 231-234

[4] Kitamura T., Kunieda M., (2014), *Clarification of EDM Gap Phenomena Using Transparent Electrodes*, CIRP Annals 63 (1):213-216

[5] Miţkevici M.K., (1966), *Ob elektro-erozionnom effekte na vibrinuişcih elektrodah, Fiziceskie osnovi elektro-iskrovoi obrabotki materiallov*, Editura Nauka, Moscova

[6] Savii Gh., Nani V.M., Militaru C., Muntean N., (1989). *Contributions on Ultrasound Activation of Wire-Cut Electric Discharge Processing*, ISEM 9, Nagoya

[7] Nani V.M., (2016). *Effect of wire electrode's ultrasonic vibration on erosive capacity to W-EDM machines*, International Journal of Advanced Manufacturing Technology, 88, 425-441

[8] Bakuto I.A., (1959). *O zavisimosti elektroerozionovo effekta at elektriskovo rejima rozriada*, Zbarnik mancinîh FRI AM, Moscova, nr. 5

[9] Okada A., Uno Y., Onada S., Habib S., (2009). *Computational Fluid Dynamics Analysis of Working Fluid Flow and Debris Movement in Wire EDMed Kearf*, Annals of the CIRP 58 (1): 209-212

[10] Juan Q., Fei Y., Jun W., Bert L., Dominiek R., (2015a). *Material removal mechanism in low-energy micro-EDM process*, CIRP Annals-Manufacturing Technology, 64, 225-228

[11] Wong Y., Rahman M., Lim H., Han H., Ravi N., (2003). *Investigation of Micro-EDM Material Removal Characteristics Using RC-Pulse*, Journal of Materials Processing Technology, 140 (1-3): 303-307

[12] Nani V.M., (2015*). Ultrasonic activation of the wire electrode on EDM processing machine*, ISBN: 978-3-659-68755-6, LAP LAMBERT Academic Publishing, Germany

[13] Snoeys R., Van Dyck F., (1971). *Investigation of EDM Operations by Means of Thermo-Mathematical Models*, Annals of the CIRP, 20 (1):35-36

[14] Hayakawa S., Sasaki Y., Itoigawa F., Nakamura T., (2013), *Relationship Between Occurrence of Material Removal and Bubble Expansion in Electrical Discharge Machining*, Procedia CIRP 6:174-179

[15] Choi J., Hsiao C., Chahine G., Ceccio S., (2009). *Growth, oscillation and collapse of vortex cavitation bubbles*, Journal of Fluid Mechanics 624:255-279

[16] Inoue K., (1977). *Fundamental of Electrical Discharge Machining*, Published by the Society of Non – Traditional Technology, Tokyo

[17] Van Dijck P.J., (1974). *Some results of physical research in EDM*, ISEM 4, Bratislava

[18] Williams E.M., (1958). *Theory of electric sparks machining*, Electrical Engineering

[19] Kurr R., (1974). *Hänge zwischen Einzelentla-dungen Energievertei lung und technologischen Kenngrössen bei der electroerosiren Bearbeitung*, Bericht der WZL-TH, Aachen

[20] Loeb L.B., Meek J.M., (ed. 1977). *The Mechanism of the Electric Sparks*, Stanford University Press

[21] Nani V.M., (2017). *Complex phenomena study in dielectric fluid from gap during the W-EDM processing in ultrasonic field*, International Journal of Advanced Manufacturing Technology, 92, 197-215.

[22] Wertheim R., Kurr R., Obaciu G., (1977). *Temperaturverteilung in Spaltbereich beine funkenerosiren Genken*, Industrie Anzeiger, no 99

[23] Raether H., (1964). *Electron avalanches and breakdown in gases*, Butterworth's

[24] Drăgan O., Iancu C., Amza Gh., Drimer D., Isarie OI., (1983). *Ultrasunete de mari energii / High energy ultrasound*, Editura Academiei RSR, București