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CONSTRUCTIVE SOLUTIONS OF AN EQUIPMENT FOR ULTRASONICALLY AIDED ELECTRODISCHARGE MACHINING OF MICRO-SLOTS

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ABSTRACT: The paper reveals the technical solutions adopted on the design of an equipment used for electrodischarge machining aided by ultrasonics of microslots. Ultrasonic assistance consists of two separate independent working sub assemblies. The main ultrasonic assistance, acting at workpiece level, consists of an ultrasonic chain containing also the electrode tool. For best performance the ultrasonic generator of this chain must be synchronized with the electrodischarge installation pulse generator. A second additional system for ultrasonic assistance supplies high pressure dielectric liquid within working gap, through cavitational effect produced by an ultrasonic chain that vibrates in an ultrasonic hopper. The equipment is able to assure adjustments of perpendicularity or specific angular position for both electrode-tool holder and workpiece holder. The equipment was designed in order to extend ELER 01 Romanian electrodischarge installation capabilities.

KEY WORDS: equipment, ultrasonically assisted microEDM, cavitational effect.

1. INTRODUCTION

There are a number of problems still to be solved to enable the EDM process to be adopted on an extensive process. . Lower material removal rate (MRR) and poor surface quality (SQ) are the major EDM process limitations. In other words, maximizing the MRR and minimizing the surface roughness value are the real time EDM process objectives.

In both EDM and microEDM processes the material is removed by successive electrical discharges occurring between an electrode-tool and the workpiece immersed in a dielectric fluid. Every discharge ionizes a very restricted area between, the closest opposing peaks of roughness of the electrodes and generates a localized plasma channel, within a vapor bubble, in which the temperature can be as high as 8.000 - 10.000 ºC by some researchers [1] and 10.000 - 20.000 ºC by others [2]. This hot plasma may lead to melting and evaporate of both electrodes.The plasma pressure has been estimated to be up to several tens of bars [3].

At the end of the pulse, when the current is stopped, the pressure suddenly falls, causing the superheated molten liquid on the surface of both electrodes to explode into the dielectric liquid, leaving a crater on the electrode surfaces and creating small solid and/or hollow debris.

After bubble implosion, no material removal is achieved because it is already solidified. In case of microEDM single discharge, the life time of gas bubble is prolonged, even after 120 µs from electrical breakdown dielectric liquid [4] , causing a great amount of material to be resolidified by the time that hydraulic forces could access the crater.

The ultrasound assistance acts in two ways: firstly, it reduces the bubble lifetime duration, allowing the dielectric liquid to more quickly enter EDM spot, when a great amount of the crater is in liquid state; secondly, the cavitational cumulative microjets creating great pressure, of 10 MPa order, develop shock waves parallel to machined surface removing micropeaks with low shear resistance, decreasing roughness.

Referring the type of pulses used for machining, commanded pulses were considered due to their properties to have better timing control than relaxation ones [5]. It was found that ultrasonic assisted EDM is effective in attaining a high MRR and a better surface quality SQ in finishing regime.

2. EDM ULTRASONICALLY ASSISTED – STATE OF ART

Several researchers have reported that ultrasonic assisted EDM improves discharge characteristics [6],[7]. Gao and Liu [8] reported that the workpiece vibration induced by ultrasonic action has a significant effect on the performance of the micro-EDM process and efficiency of the ultrasonically aided micro-EDM is up to eight times greater than conventional micro EDM. The workpiece ultrasonic vibration is a hard task to obtain due to resonant frequency achievement of both workpiece and workholder device. Murthy [6] showed that ultrasonic assisted EDM significantly reduced inactive pulses, fact which conduct to a higher material remove rate - MRR. Zhixin et al. [7] reported that for machining of advanced ceramics, the combination of ultrasonic machining and EDM may provide a higher MRR. Also Lin and Yan [8] have pointed out that EDM of hard titanium alloy by using ultrasonic tool vibrations give higher MRR and eliminate the recast layer.

In ultrasonically assisted EDM, it is recognised that the role of the acoustic wave and cavitation phenomena is to improve the flushing and material removal from the surface craters. These process conditions are significant for micro drilling and production of slots and grooves. The vibrating movement of the electrode tool improves dielectric liquid circulation and the pumping action by pushing the debris away and sucking new fresh dielectric, providing ideal conditions for discharges and additional material removal, even in solid state, in cumulative microjets stage.

The literature survey on achivements obtained in researches conducted on EDM ultrasonically assisted can be synthesized by the following conclusions:

- machining rate can be increased several times with ultrasonic-aided machining operation when compared with conventional microEDM;
- better surface finish can be achieved by an ultrasonic vibration assisted tool;

- tool wear rate may be considerably reduced;
- ultrasonic vibration gives pressure variation all along the gap and results in better flushing, debris removal, circulation of dielectric and increases the process stability;
- an enhancement of molten metal ejection from the surface of the work piece, due to gas bubble lifetime reduction and by the mechanical effect of cavitational gas bubbles implosion.

3. TEORETHICAL ISSUES ON ULTRASONIC ASSISTANCE OF EDM

For microEDM ultrasonically assisted the electrode-tool vibrates on vertical axes (pure longitudinal waves) with ultrasonic frequency, usually 20 kHz (can be also 40 kHz or even more). Consequently, cavitational phenomena are induced mostly in the frontal gap.

An acoustic pressure (p_{ac}) is created within dielectric liquid, which can be calculated with the relation:

$$p_{ac} = 2\pi \cdot c \cdot \rho \cdot f_{US} \cdot z \qquad \text{[MPa]} \qquad (1)$$

where: c is sound velocity in dielectric liquid [m/s]; ρ - density of dielectric liquid [kg/m^3]; f_{US} - ultrasonic frequency [Hz] and z - electrode elongation [m], given by the relation:

$$z = A \sin \omega t \qquad \text{[m]} \qquad (2)$$

where: A is oscillation amplitude [m]; $\omega=2\pi f_{US}$ [s^{-1}].

Total hydrostatic pressure (p_{ht}) also takes into account the local pressure (p_h) from the gap:

$$p_{ht} = p_{ac} + p_h \qquad (3)$$

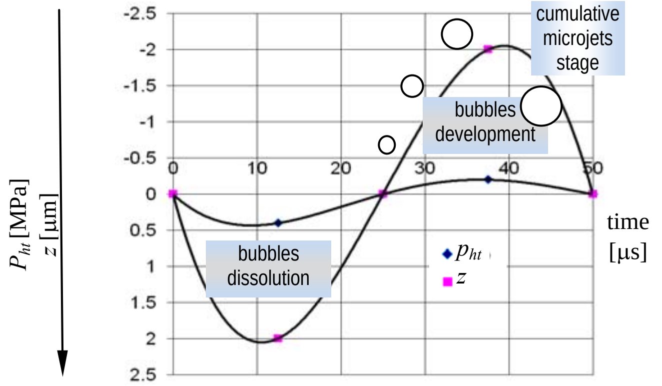

Figure 2. Hydrostatic pressure variation and tool elongation within one ultrasonic period (*f_{US}=20kHz)*

The p_{ht} pressure variation along the elongation z is represented in fig. 2, based on relations (1-3), an amplitude of A = 2 μm is enough to create cavitation.

In case of total shutting down of gas bubble, Rayleigh provided the relation for calculation of implosion time (τ):

$$\tau = 0{,}915 R_m \sqrt{\frac{\rho}{p_h}} \qquad \text{[s]} \qquad (3)$$

where R_m is maximum of bubble radius, depending on half ultrasonic period, $T_{US}/2$.

It can be noticed, on fig.2, that capillary phenomena are produced in two semiperiods: liquid compression (bubbles dissolution in dielectric liquid) and liquid stretching (bubbles development) until cumulative microjets stage occurs. At each final stretching semiperiod, that lasts 25 μs in this case, collective implosion of bubbles from the gap is produced due to p_{ht} increase. Machining under difficult conditions, like finishing operations working with narrow gap needs flushing with high pressure. Ultrasonic aiding provides necessary pressure to evacuate removed particles from the gap, leading to EDM process stability.

4. CONSTRUCTIVE SOLUTIONS

The equipment for ultrasonically aided electrodischarge machining of microslots, presented in this paper, consists of three different functional distinctive parts as shown in figure 2, where 1- tool holder and orientation device; 2- additional ultrasonic flushing device 3- workpiece holder and orientation device [12].

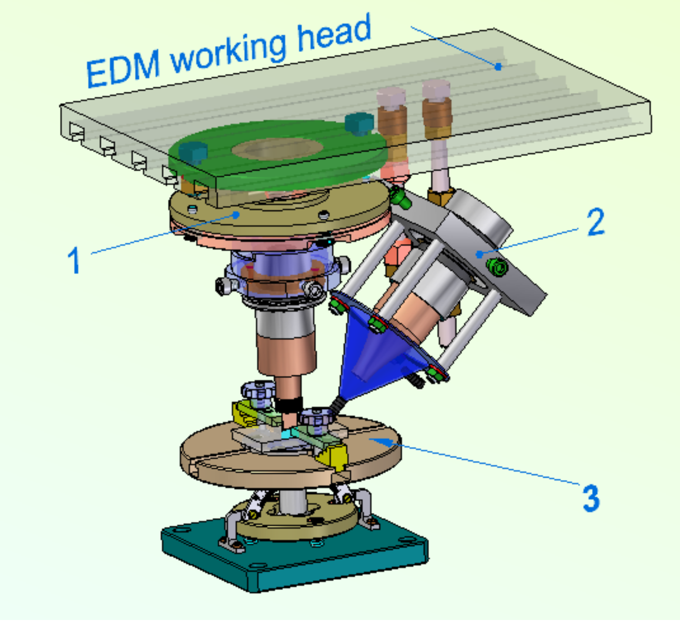

Figure 2. Major constitutive parts of the equipment

4.1 Tool holder and orientation device

The main function of this subassembly are: to support the accoustic chain, including the electode tool, to permit verticality adjustment of the tool and to have the capability of adjusting angular position of the slot in horizontal plane.

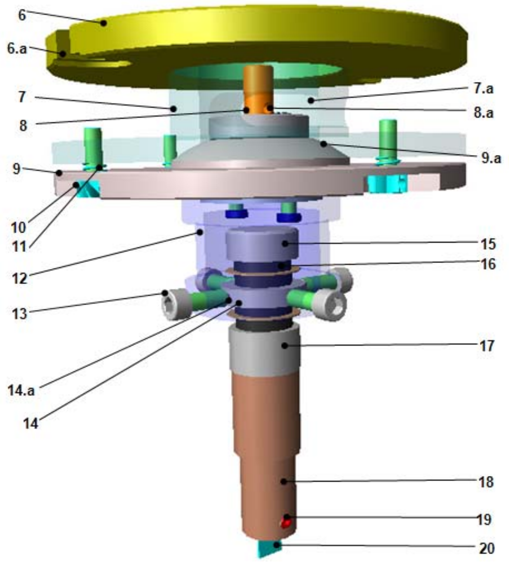

Figure 3. Tool holder and orientation device

Constructive solution is presented in figure 3., with all components numbered. At the top of the assembly we can notice a base flange ***6*** which assures the screwed connection with the working head of the EDM installation. Forming a rigid assembly with pos. ***6*** we ca notice a fixed flange ***7***. Mounted on a hemispherical joint pos. ***9a*** we can notice the tiltable flange ***9***. Verticality adjustment can be obtained acting on the four special screws ***10***. Helical springs ***11*** creates a pretension force to insure a greater precision of adjustment.

Angular position of the electrode, in horizontal plane, can be obtained by rotating the cilindrical shell containing the ultrasonic chain, using the angular position scale ***9c*** (see fig. 5)

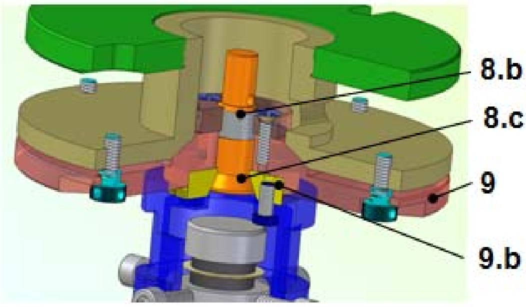

Figure 4. Locking mechanism detail

In order to preserve the desired position of the electrode tool a locking mechanism is shown in figure 4. Acting on special conical head screw ***8***, we can lock or unlock the mechanism, in order to block or to adjust the position.

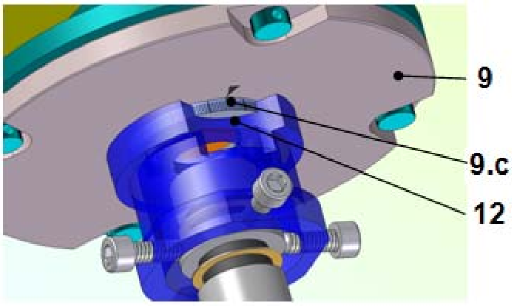

Figure 4. Angular position scale detail

The accoustic chain is mounted on cilindrical shell ***12*** using four Allen screws. It is to be mentioned that the accostic chain is mounted on a nodal flange, in order to avoid any power loss.

Electrode tool, usually made of copper, is locked on the stepped horn by the slotted screw ***19***.

4.2 Workpiece holder and orientation device

The main functions of this device is to mantain workpiece in position during machining process and to allow angular positioning of the workpiece. As we mentioned before machining forces can be considered negligible, so the clamping forces have minimal values. A general view of the device is presented in fig. 5. On a base plate ***21***, a spherical joint is created with the pivot ***22***, allowing the entire assembly formed by the pivot with the workingplate ***25*** to rotate.The maximum angle is about 50^0 in each side, allowing 1^0 precision.

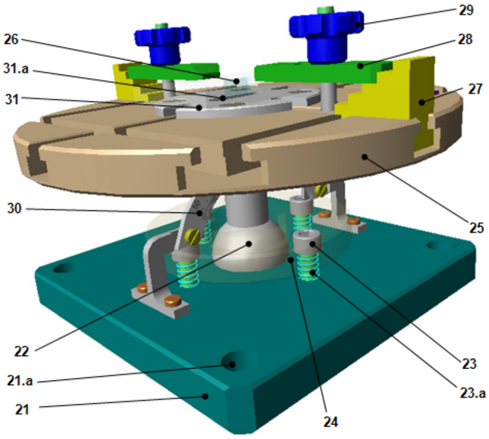

Figure 5. Workpiece holder and orientation device

In order to mantain the adjusted position by a special lid ***22*** which can be tighten or released using the four Allen screws ***23***.

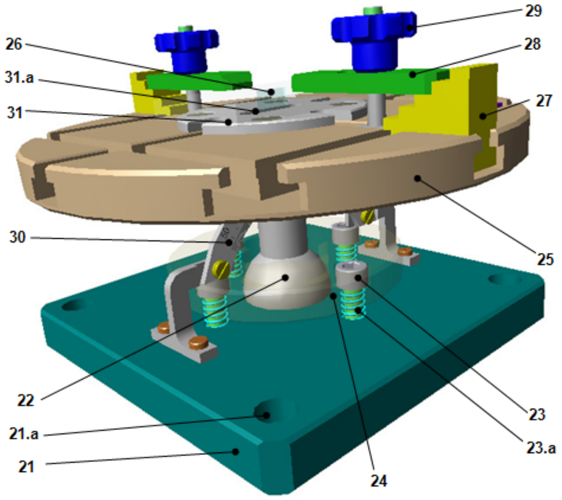

Figure 5. Workpiece holder and orientation device

The position of the workpiece is preserved by two clamps ***28*** and by acting on the two screwed bows ***29*** the clamping force can be apllied or removed.

Figure 6 shows the final optimised construction, partially sectioned.

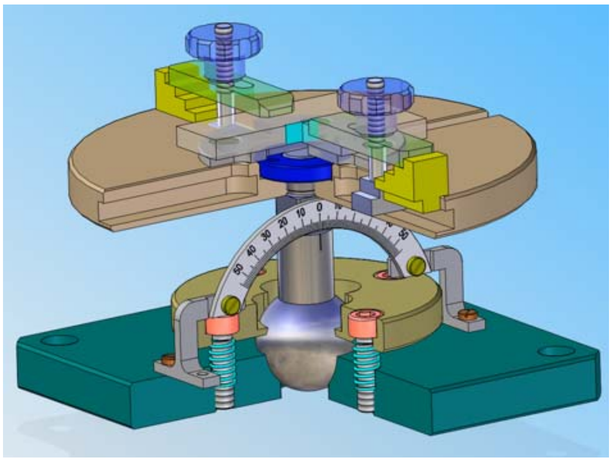

Figure 6. Workpiece holder and orientation device partially sectioned (final design)

4.3 Additional ultrasonic flushing device

The additional ultrasonic device cosists of the following major parts: a base flange ***37*** which supports the ultrasonic chain and also the funnel (see fig 7 & fig.8).

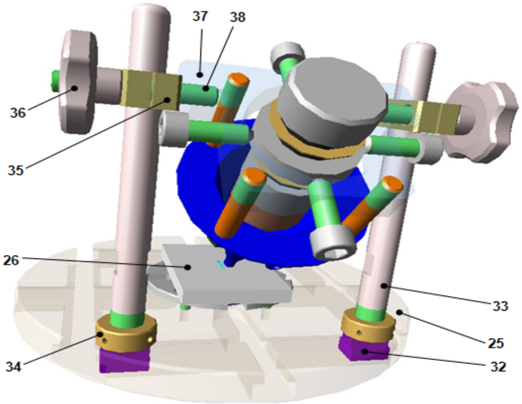

Figure 7. Initial constructive solution for additional ultrasonic flushing device (view 1)

The ultrasonic horn is partially submerged in dielectric liquid. The dielectric liquid is from the EDM pumping installation is delivered thru nozzle ***44***.

The cavitational fenomena accurs in the liquid contained in the funnel, so through nozzle ***46*** dielectric liquid containing cavitational bubbles is delivered to working gap. It is known that even that the cavitational gas bubbles last a very short time, the implosion of a bubble initiates a new cavitational effect so if the nozzle is in working gap proximity there are notable effects.

In order to adjust the relative position of the outwards nozzle the equipment has two screwed bows ***36*** acting on special slotted locking parts. The supporting columns ***33*** mounted on the working table of the workpiece holder and orientation device allows positioning the nozzle ***46*** as close as possible from working gap (avoiding any electrical contact).

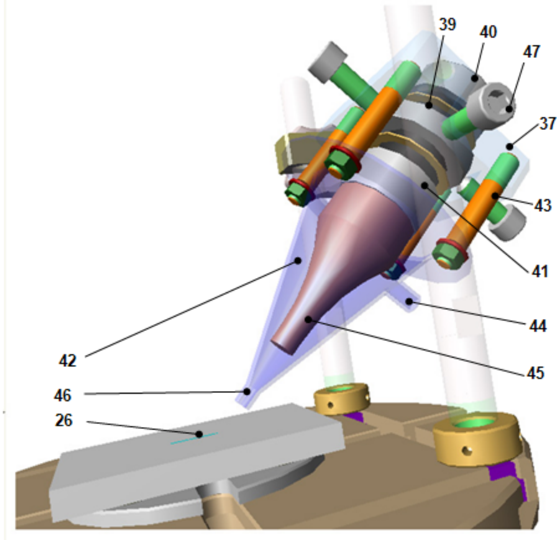

Figure 8. Initial constructive solution for additional ultrasonic flushing device (view 2)

4.4 Equipment construction optimisation

Functionality test carried out on a prototype revealed some limitations regarding especially accessibility of the workpiece.

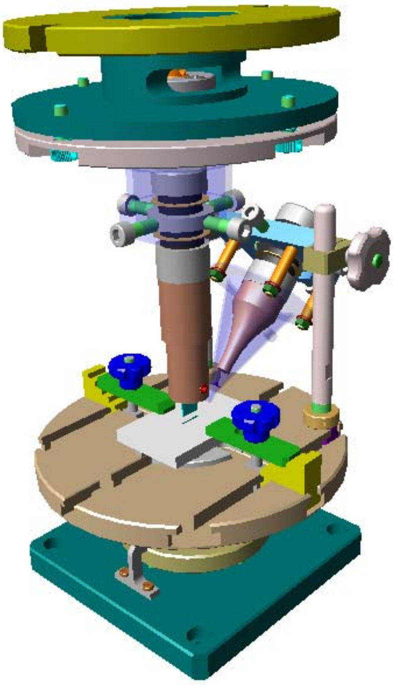

Figure 9. Initial design of equipment [12]

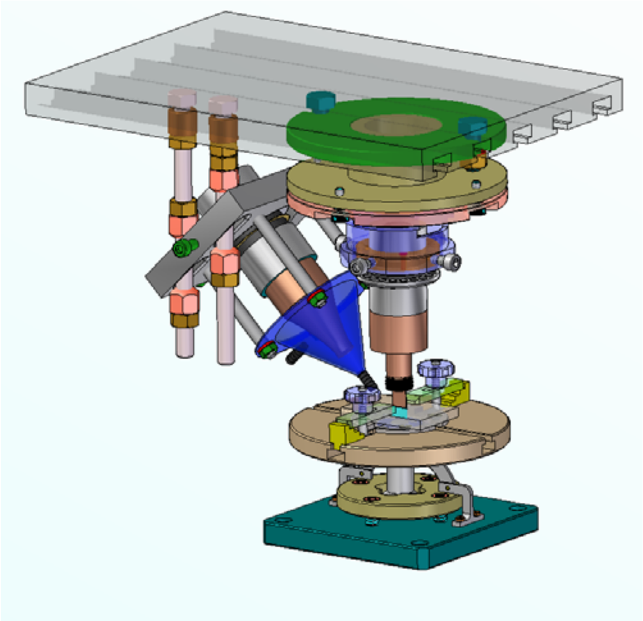

Figure 10. Final optimised construction of thev equipment

The initial constructive solution (as seen in fig. 9) was to mount the additional ultrasonic flushing system on the worktable ***25*** (see fig. 5). The mentioned solution limits the access to the workpiece and demands quite frequent adjustments on the position of ultrasonic funnel. Restricted access was revealed also when positioning the workpiece, so in many cases the additional system has to be dismount.

So to gain full access on the workpiece we considered an alternative optimised design (see fig. 10), where the ultrasonic flushing system is mounted on the EDM installation working head.

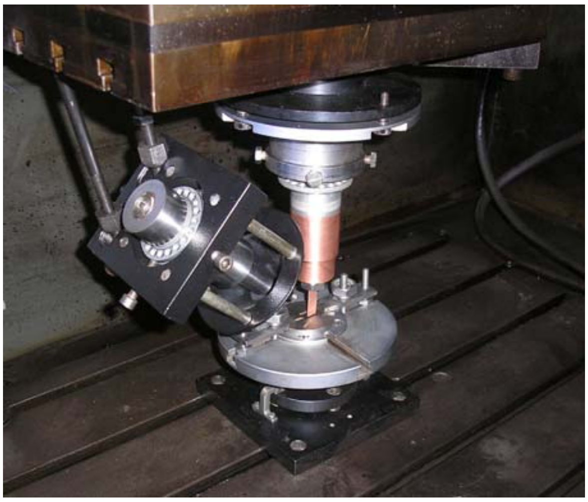

Figure 11 Photo of the equipment mounted on ELER 01 Romanian EDM installation

In figures 11 & 12 is shown the experimental fully functional prototype, on which functionality, positioning precision and machining tests were carried out. The tests revealed that workpices can be manufactured usually on IT6, IT7 precision class, using conventional measuring tools for adjustments. Better results may occur if adjustments are made using combined adjustment techniques (eg. optical and mecatronic).

Regarding the ultrasonic assistence we have noticed that the temperature of the PZT transducer reached over 75^{o}C (at a 28^{o}C ambiental temperature).

Knowing that the oscilation frequency of the transducer is very sensitive with variations of temperature, a cooling system might be necessary. This issue can be easily be solved by instaling a n air fan blower in order to mantain a constant temperature. The system can be equipped with a thermostatic device in order to automate this function.

Figure 12. Photo of the equipment mounted on ELER 01 without additional ultrasonic flushing device

5. PRELIMINARY EXPERIMENTAL RESULTS

Some preliminary experimental data were carried on ELER 01 Romanian EDM installation in order to study the effect of ultrasonic assistance. Micromachining was performed with electrode-tool and workpiece having no flushing holes inside them aiming at microslots generation. In the first stage, the experiments were carried out using only additional ultrasonic assistance. Using this technique is much cheaper, with no modification on an existing EDM installation. The power used to actuate the acoustic chain was $p_{cus}=120w$ at an ultrasonic frequency of $f_{us}=40\ khz$. The power to actuate the acoustic chain can be much greater as long as the acoustic chain amplitude was not restricted by the working gap size; at this time, the PZT transducer part of the prototype was not able to support values of power greater than that used during these preliminary experiments. The advantages of the equipment are: a simple construction of the acoustic chain, because the dielectric liquid is supplied in a funnel separate from the acoustic chain; the resonance condition is easier to achieve because the concentrator has no holes for dielectric supply; the pressure loss is reduced by inclination of the acoustic chain, aiming to short the distance between the cavitation place and the working zone, using a hose that brings the dielectric to working gap; great power to actuate the acoustic chain can be used, without interfering with the elements of the technological system; the evacuation of removed particles from the gap is improved; additional ultrasonic removal mechanism determines the machining rate increase; the shock waves are favourably oriented along the working gap; the gas bubbles from the gap collapse much earlier than in classic EDM and thus the dielectric liquid can find material in liquid state and consequently the machining rate grows

We observed that using cavitation ultrasonically induced at lateral flushing (by using the additional ultrasonic assistance), an increase of 20...30% on MRR can be achieved beside an improvement of surface quality.

In order to study the effect of cavitation ultrasonically induced in working gap we used a X210CR12 material workpiece. In these preliminary experiments we used commanded pulses and the following working parameters: current step $I=0.8A$, pulse time $t_{on}=12\mu s$, pause time $t_{off}=6\mu s$.

The geometrical mean dimensions obtained at microEDM and microEDM+US machining are presented in table 1.

Table 1. Craters mean dimensions [μm]

Crater mean dimensions	micro**EDM**		micro**EDM+US**	
	Depth	Radius	Depth	Radius
	3.6	4	1.6	3.2

This synchronization between discharges and tool elongation could increase machining rate more than 5 times.

Also efficient is the removal mechanism by ultrasonic shock waves, decreasing roughness up to 50% by cutting microgeometry peaks. The optimum power to actuate US chain must be experimentally found for each machining type.

As we mentioned before the additional ultrasonic flushing device working parameters are not critical ones, the only condition to be respected is the existence of cavitational effect. Regarding the power to actuate the ultrasonic chain is limited to maximum PZT transducer capability power. Of course there are some dimensional limits, but they are not critical.

The critical element on ultrasonic assistance is the main ultrasonic chain. Ultrasonic chain consists in a typical transducer sandwhich piezo-electric (PZT) ceramics center-bolt (Langevin) design and a stepped ultrasonic horn. Ultrasonic transducer converts the electrical wave to mechanical vibration which is relative small and must be amplified using an acoustic horn. The main function of the horn is to amplify the vibration amplitude of the tool to the level required for effective machining assistance, but it serves also as means of transmitting the vibrational energy from the transducer [9].We mentioned that the ultrasonic power is very sensitive related to manufacturing conditions. Less power can conduct to a lower acoustic pressure causing low or even absence of cavitational effect. Greater power can conduct to a damaged surface so it is important to determine the optimal ultrasonic power. Based on our experimental data this power must be between 100 to 400W. Another important parameter of ultrasonic assistance is the electrode oscillation amplitude. For finishing microEDM operations the working gap is nearby 10μm in width. From previous research work [10] we have determined that for microEDM the required amplitude is near 1/5 of working gap width. We also established that a stepped ultrasonic horn is the optimal solution from both technical and economical reasons.

So we can conclude that the main aspects of the ultrasonic assistance in successive order are:

- maximum transfer of active power from the ultrasonic generator to the ultrasonic transducer;
- minimization of the power consumption of the transducer;
- optimization of the transformation from the electric energy transducer of excitation into mechanical-elastic .oscillating energy.

The maximum transfer of active power from the electric switching signal generator to the ultrasonic transducer takes place when the signal frequency of excitation is equal to the mechanical resonant frequency of the transducer at work. This frequency isn't fixed, paradoxically, it is variable within its limitations around its nominal values and equal with the frequency of the sonotrode.

The solution, resolving this issue, consists in the possible creation that the oscillating frequency of the generator to follow permanently the frequency of mechanical resonance of the transducer through a process called ***ultrasonic reaction***. This has an action at the beginning of the machining process, but the signal excitation frequency cannot be equalized permanently with the mechanical resonance frequency [11].

It is very important to know the resonance frequency and amplitude at every point of the ultrasonic horn, in order to: precise determination of the nodal plane position for locking in place of the ultrasonic system for desired processing; the parameters of the ultrasonic system can be correlated with technological parameters, especially at EDM+US, in order to avoid short-circuits between electrode-tool and workpiece; finite element method allows testing of various shapes and dimensions of ultrasonic horns without the need to manufacture a real prototype; it allows the correct selection of the horn shape and dimensions for a particular machining process demands. It is also important the selection of horn material for desired amplitude of vibration.Finite Element Method - FEM simulation becomes thus a very powerfull and useful tool. If the FEM has been performed properly, then the performance predicted by FEM should agree reasonably with the real sonotrode performance.

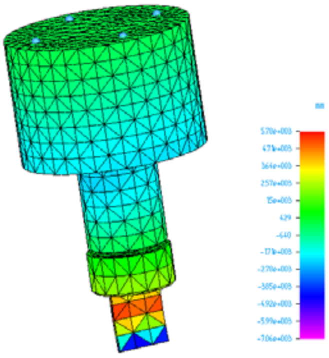

Figure 13 FEM simulation of sonotrode

From our previous studies, it was established that the stability of EDM+US finishing process was obtained increasing the working gap through ignition voltage growing and amplitude decrease of US oscillations.

FEM modelling of sonotrodes enables design time and manufacturing costs to be effectively reduced in practical EDM+US technological system achievements. Several runnings were carried out on varios dimensions of ultrasonic horn and electrode tool – blade shaped (see fig.13).

6. CONCLUSIONS

The results revealed two important things:

1. for microEDM manufacturing, due to large differencies on cross sections of ultrasonic horn and electrode tool, it have been noticed that the electrode tool shape and dimensions have negligible influence on sonotrode resonant frequency. Based on this fact we can estimate that we can use the same sonotrode for different workpieces, changing only the electrode tool. Further researces are needed to design a proper tool holder device or a changing system
2. on blade shape electrodes shape, fom FEM simulation, we have noticed that the electrode blade have additional oscilattions (depending on blade dimensions). Buckling type or torsional additional oscilations had been noticed. Thus the amplitude is relative small, it can have a great influence on precision of machined part. Further researces are needed in order to consider these fact on electrode-tool design.

The EDM+US method can be used when the fabrication volume is large enough to justify the corresponding additional expenses and longer manufacturing preparation.Then it can be concluded that EDM+US becomes economically efficient over a certain number of workpieces; our preliminary estimations reveals that the fixed manufacturing costs for EDM+US manufacturing are at least two times greater then EDM fixed costs, due to necessary up-to-date installation modifications.

Further researches will be focused on synchronizing the EDM and ultrasonic generators and to improve flexibility of EDM+US technology.

We also intend to use a computer integrated, fully functional, machining system to achieve fast manufacturing elements of acoustic chain and electrode design in order to decrease the response time related to new workpieces manufacturing preparation.

7. ACKNOWLEDGEMENTS

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