

INNOVATIVE SOLUTIONS FOR PERFORMANCES INCREASE AT MICRO-ELECTRICAL DISCHARGE MACHINING AIDED BY ULTRASONICS

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ABSTRACT: The paper deals with researches aiming at increase of technological performances at micro-electrical discharge machining aided by longitudinal ultrasonic oscillations of electrode-tool (µEDM+US). Some essential issues of complex phenomenology of µEDM+US, experimental results obtained so far, and some appropriate strategies for material removal process are presented. Finite Element Method (FEM) applied at µEDM+US in connection with strategies to be followed is approached. Patented solutions for equipment dedicated to µEDM+US used at WEDM, microslots, and deep microslots machining are presented.
KEY WORDS: Micro-electrical discharge machining, ultrasonics, Finite Element Method, patents.

1. INTRODUCTION

Micro-machining defines the processes that achieve products in the range of 1 to 999 µm, according to CIRP committee of Physical and Chemical processes. The present trend of ultra miniaturization led to µEDM applications, microscopic mechanical components and devices. In this respect, the µEDM technology is helpful for precision machining as well as for micro-components, and filigree structures up to 5 µm. A large range of products can be achieved like fuel injector valves, parts and components for medical devices, micro-moulds, stamping tools, micro-electronic parts etc. [1].

Ultrasonic vibrations of electrode-tool and workpiece were applied successfully in specific cases to increase performances at microEDM as several researchers reported. The vibration of tool electrode or workpiece improves dielectric circulation by pushing removed particles from the gap and sucking cleaned dielectric, which provides efficient discharges and higher removal rate [2]. Ogawa et al. reported out that the depth of micro-holes by the combined effect of EDM with ultrasonic vibration becomes almost two times greater than without ultrasonic vibration and machining rate was increased [3]. Wansheng et al. demonstrated that holes with diameter less than 0.2 mm and the aspect ratio more than 15 can be produced without difficulty by ultrasonic vibration, using micro-EDM [4]. Yan et al. reported that with combined effect of µEDM and micro-ultrasonic vibration, the diameter variation of microholes between the entrance and exit was about 2 µm at diameters of about 150 µm and depth of 500 µm [5]. Gao and Liu found that efficiency of ultrasonic aided µEDM is 8 times greater than classic µEDM at workpiece ultrasonic vibration of 0.5 mm thickness from steel and 45 µm electrode from tungsten [6]. H. Huang at al. achieved spectacular increasing of machining rate up to 60 times at µEDM+US of microholes in Nitinol, an intelligent material from Ni and Ti alloy, which keeps the shape after deformation and reheating [7]. J.C. Hung at al. combined ultrasonic vibration with electrode-tool rotary movement at microholes machining [8].

Nevertheless ultrasonic aiding supposes additional costs to achieve the US chains and the generator, including relative high time consume for fabrication preparation related to resonance condition achievement, which could be covered at higher volume of fabrication, against classic EDM.

2. ESSENTIAL PHENOMENA AND IMPROVEMENT STRATEGY OF EDM+US

The US oscillation period comprises a semiperiod of dielectric liquid compression from the gap (capillary phenomena) and a stretching semiperiod (fig. 1).

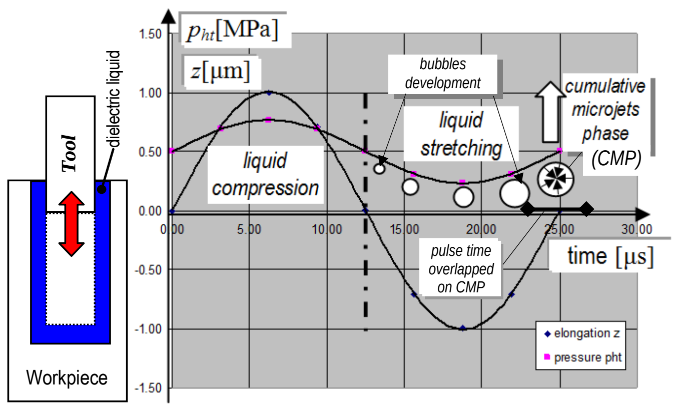


Figure 1. Ultrasonically induced cavitational phenomena in the gap at µEDM+US (frequency = 40kHz, amplitude of tool oscillations = 1 µm, density of dielectric liquid = 840 kg/m^3)

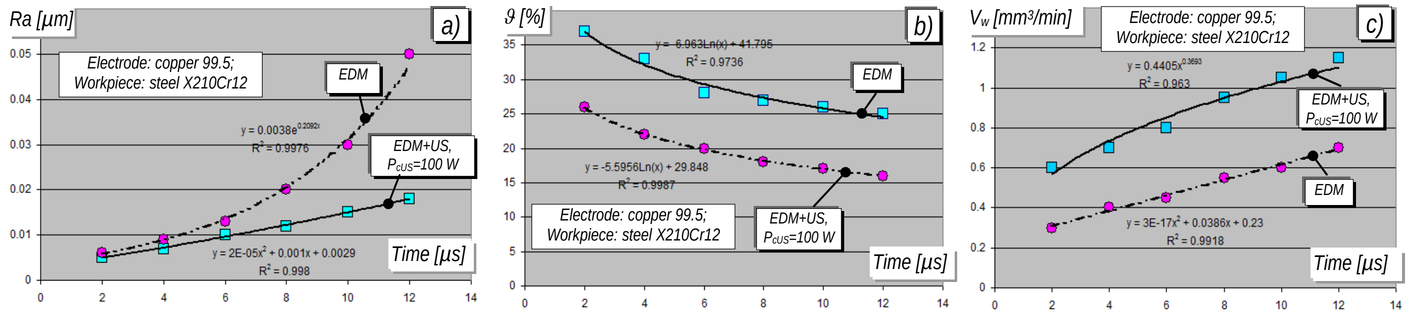


Figure 2. Comparative experimental data at EDM and EDM+US micromachining with random pulses overlapping on CMP

At ultrasonic period end, after the gas bubbles from the gap continuous development, the bubbles will collapse after increasing pressure within the gap, occurring *Cumulative Microjets Phase* (CMP). So, delivering pulses in the second semiperiod is very favourable, even rather overlapping them on *CMP*. This allows hydraulic forces to find material still in liquid state and remove it much more than at classic EDM. In classic case, due to long life of gas bubbles after pulse end, the melted material is already resolidified after van Dick's model [9], confirmed by high speed framing camera images [10].

In fig.1, the total hydrostatic pressure p_{ht} is calculated with the relation:

$$p_{ht} = 2\pi \cdot c \cdot \rho \cdot f_{US} \cdot A \sin \omega t + p_h \quad \text{[Pa]} \qquad (2)$$

where: c is sound velocity in dielectric liquid; ρ - density of dielectric liquid [kg/m^3]; f_{US} - ultrasonic frequency [Hz]; A – amplitude of elongation z [m]; $\omega = 2\pi f_{US}$ [s^{-1}]; p_h - local pressure [Pa].

The resulted shock waves oriented along the machined surface (along the gap) evacuate the EDM products (workpiece particles) from the gap and remove the micropeaks (margins of the craters of previous discharges), thus decreasing the machined surface roughness.

Ultrasonic generator with automatic control of frequency based on programmable micro-processor; due to short EDM pulse duration, 40 KHz frequency moves *CMP* closer to pulses ends than 20 KHz one, taking more advantage on it, in terms of material removal. When the pulse is overlapped on cumulative microjets stage, it is possible to remove material in liquid state, but this probability is low due to very short duration of pulses. The probability is greater to remove the craters margins in solid and plastic state, because cumulative microjets phase comes relative close to pulses delivered within stretching semiperiod. Moreover at 40 kHz all ultrasonic chain lengths are twice shorter than in case of usual 20 kHz, being multiple of half wave length $\lambda/2$ ($\lambda = c/f_{US}$). So, 40 kHz variant is appropriate to dimensional range of micro-EDM equipment, framing in miniaturization trend.

2. EXPERIMENTAL RESULTS

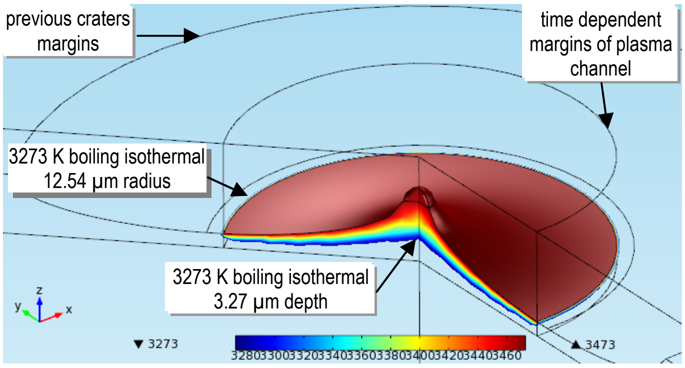
In our pilot comparative experiments of EDM and EDM+US on ELER 01 Romanian machine with specialized generator, we used 0.8 A current step, with cylindrical electrode-tool of 0.8 mm diameter from copper, X210Cr12 steel workpieces, consumed power on acoustic chain, P_{cUS}=100 W, only with random overlapping of EDM pulses on *CMP*.

Based on FEM modelling, validated through experimental data, all the output technological parameters of EDM, from fig. 2 - machined surface roughness (a), volumetric relative wear (b), and machining rate (c) - were improved by ultrasonic assistance against classic EDM in the same working conditions, at certain finishing modes using different specific equipment. These are also based on several optimization conditions of input working parameters [11].

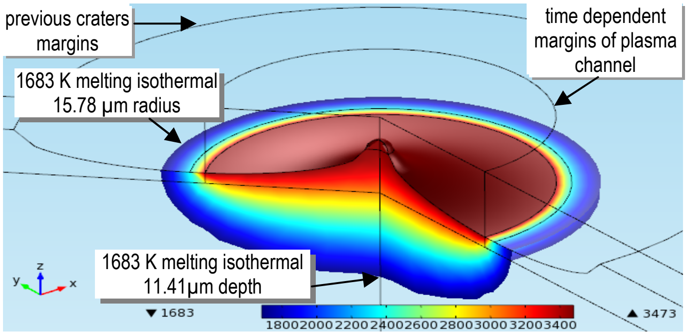
3. FEM MODELLING RESULTS

The effect of its two components, thermal and cavitational of the EDM+US process on the material (X210Cr12) removal mechanism was modelled using Comsol Multiphysics with Time Dependent Heat Transfer in Solids, and respective Structural Mechanics modules. In case of thermal component, melting isothermal was considered at EDM+US, as limit of the volume removed by discharge.

Time dependent radii of plasma channel and bubble gas around plasma channel were also introduced in the actual model frame, based on Kyoshi Inoue's model [12], found as the most appropriate [13], in accord with experimental results provided by high speed framing camera images [10]. The comparative results at EDM and EDM+US about the volumes removed by single discharge are presented in fig. 3. The FEM results proved that overlapping the EDM pulse time on Cumulative Microjets Phase, even when this is produced after a time interval less than 1 µs from pulse beginning, produces a spectacular increase of machining rate. The depth of removed crater by single discharge is more than three times greater than corresponding one from classic EDM.



a) Volume removed by 6 μs pulse time at classic micro-EDM, bordered by boiling isothermal



b) Volume removed by overlapping the pulse time on cumulative microjets phase after 0.8 μs from pulse start

Figure 3. Comparative volumes removed by single discharge at micro-EDM and EDM+US

In classic EDM, the life time of gas bubble lasts much longer than pulse time end, but at EDM+US, *CMP* is able to stop the discharge as our experiments pointed out due to high pressure developed of 100 MPa order of magnitude. So, hydraulic forces of dielectric liquid, accessing EDM spot can remove the material that is still in liquid state.

The results of FEM modelling of material removal in lateral working gap by ultrasonics action are presented in fig. 4 in case of microhole produced by electrode of 0.1 mm diameter.

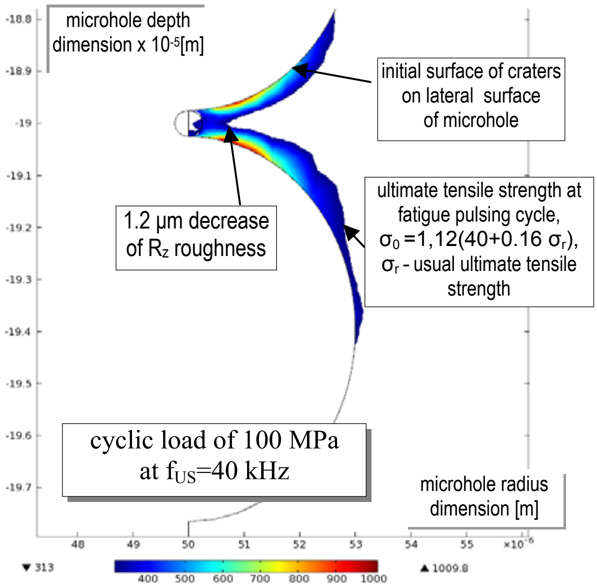


Figure 4. Von Mises stress [MPa] in X210Cr12 steel produced by cumulative microjets at EDM+US microdrilling

FEM results presented above are in agreement with experimental data, validating the model [14].

4. INNOVATIVE SOLUTIONS FOR EDM+US DEDICATED EQUIPMENT

Some innovative solutions were adopted at construction of dedicated equipment for microEDM+US.

The device for ultrasonic aiding of wire electrodischarge machining can be easily mounted on any WEDM machine in order to improve: machining rate, precision, and surface quality [15]. Its novelty consists in: vibrations in the deionized water (dielectric liquid) to produce cavitation and not of the wire or workpiece as previous solutions do; shortening the distance between cavitation place and working zone by device leaning for decrease of pressure losses; cavitation occurs within a hopper that allows high acoustic pressure (amplitude) - no contact with the wire or workpiece.
The device main elements are presented in fig. 5.

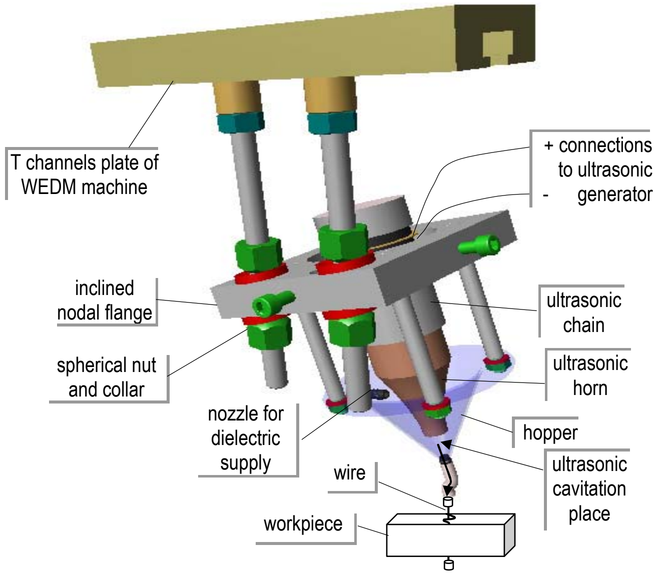


Figure 5. Device for ultrasonic aiding of wire electrical discharge machining

The novel solutions have the following advantages: precision increasing due to good evacuation of particles from the gap through high acoustic pressure ultrasonically induced, thus avoiding instability of WEDM process; the relative position between wire and workpiece is not modified by oscillations since any component of acoustic chain has no contact with wire – workpiece couple; simple construction with no holes within acoustic horn, additional reason to easily get the resonance – equality between own frequency of acoustic horn with PZT transducer subassembly; device inclination contributes to decrease of pressure losses; quality increase due to cumulative microjets orientation, parallel to machined surface and along the wire; reducing of surface roughness and white layer.

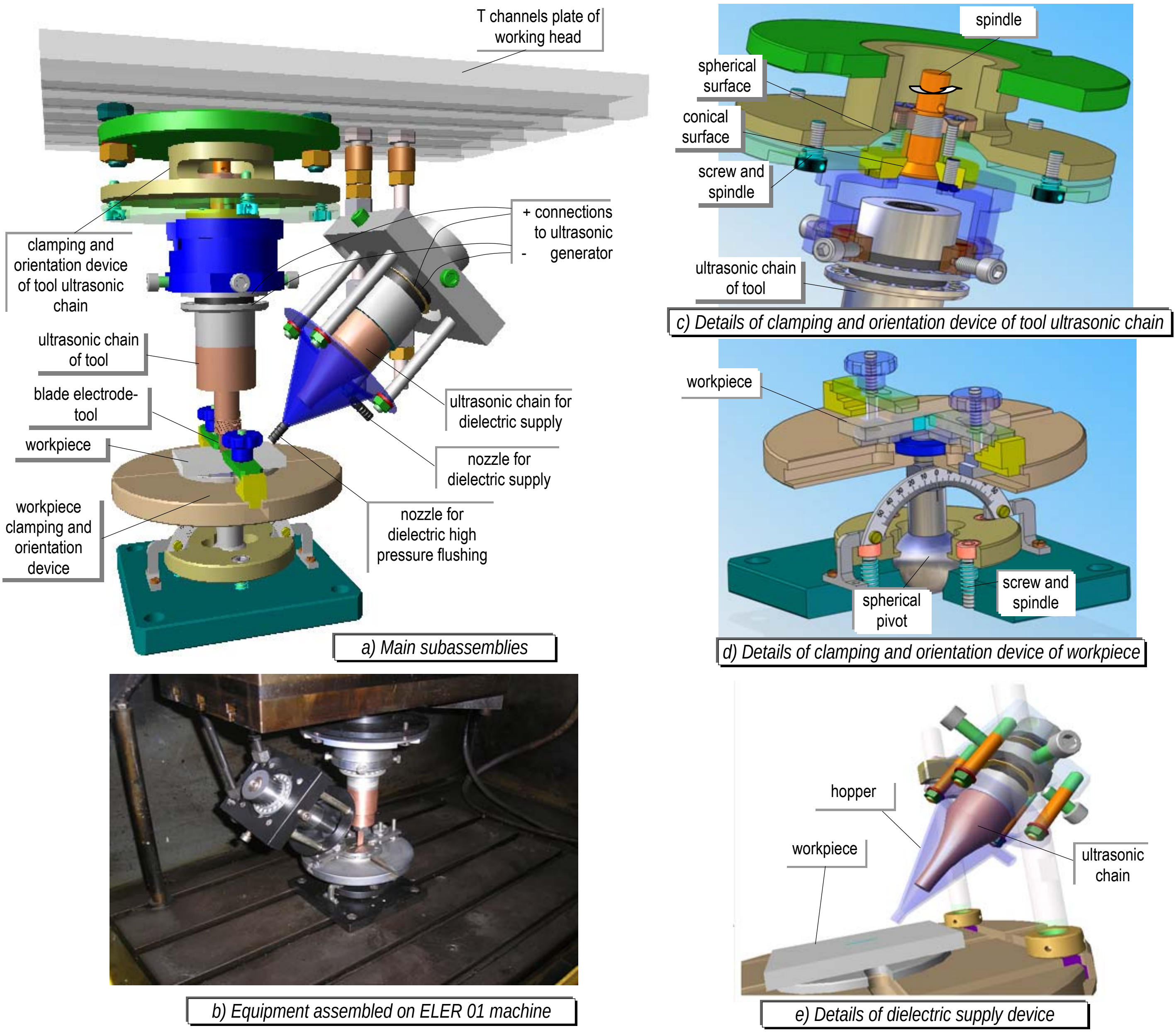


Figure 6. Equipment for ultrasonic aided electrical discharge machining of micro-slots

The equipment for ultrasonic aided electrical discharge machining of micro-slots is presented in fig. 6 [16]. The main subassemblies are presented in fig. 6.a. The equipment is easily assembled on any EDM machine, as it can be seen in fig. 6.b., using T channels plates. In fig. 6.c, some details are shown of clamping and orientation device of tool ultrasonic chain, achieving inclination, perpendicularity, and angular position of tool. Similar device for workpiece is presented in fig. 6.d, which accomplishes workpiece inclination and perpendicularity. In fig. 6.3.e, the device for high pressure dielectric supply is presented.

When machining microslots under classic conditions, EDM instability occurs due to very narrow working gap. Ultrasonic aiding, through high pressure of dielectric supplying due to ultrasonic cavitation, improves removed particles evacuation from the gap reducing short-circuits, and consequently the main technological parameters, mainly machining rate and surface quality.

Its specific construction leads to several advantages: under some optimization conditions of working parameters, it can increase machining rate up to 500% against classic EDM; no holes for flushing inside workpiece or electrode-tool needed; achieving great inclination of pierced and unpierced micro-slots; adjusting perpendicularity and angular position of electrode-tool relative to workpiece.

The novelty of equipment consists in: cumulating the effects produced by vibrations of ultrasonic chain including the electrode-tool and of ultrasonic chain for dielectric supply acting at workpiece level; high pressure supplying of dielectric liquid within working zone through cavitational effect produced by an ultrasonic chain that vibrates within a hopper; Simultaneous inclination and rotation both of blade electrode-tool and workpiece.

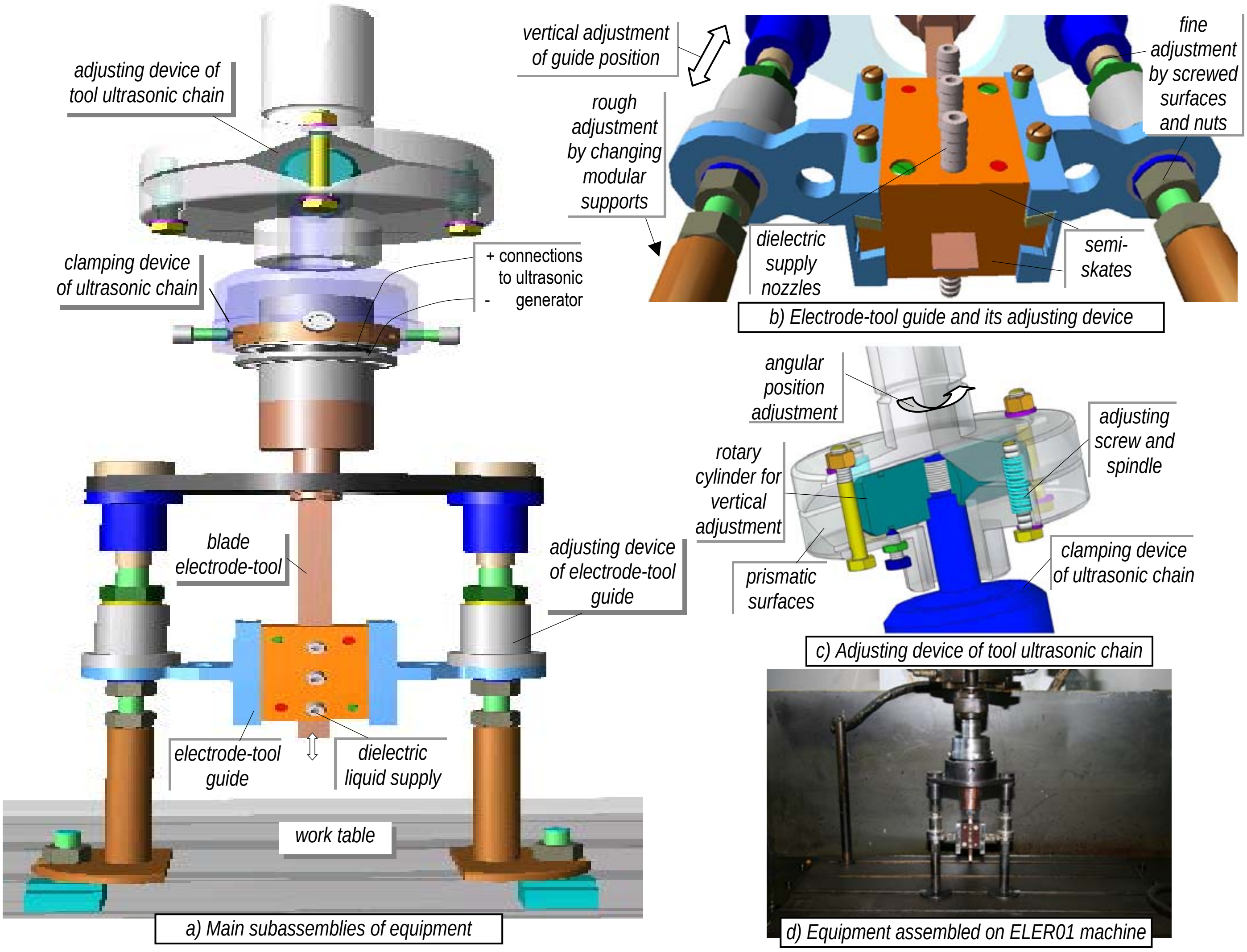


Figure 7. Equipment for ultrasonic aiding electrical discharge machining deep microslots

The variant of equipment appropriate for deep micro-slots is presented in fig. 7 [17]. Its main subassemblies are shown in fig. 7.a, the equipment being easily assembled on any EDM machine as it is presented in fig. 7.d.

Taking into account the susceptible deformations of blade electrode-tool during the machining process, a guide subassembly is conceived (fig. 7.b), comprising basically two semi-skates with low friction coefficient, and channels for lateral flushing. The guide position of tool-electrode guide can be roughly and finely adjusted on vertical direction in order to obtain the optimum position of tool against machined surface. The adjusting device of ultrasonic chain containing the tool is presented in fig. 7.c. Thus the angular position as well as the vertical position of electrode-tool can be achieved, assuring the needed micro-machining precision.

The construction of equipment led to the some advantages: machining deep micro-slots without necesity to provide holes for dielectric flushing inside workpiece of electrode-tool; growing of machining precision most of all at great depths by passing the electrode-tool through guiding assembly above or beneath the workpiece; appropriate flushing with dielectric liquid of lateral side of electrode-tool, through several flushing holes achieved inside the guiding; it assures the adjustment of perpendicularity of longitudinal axis of blade shape electrode-tool against frontal surface of machined workpiece, and angular position of electrode-tool in frontal plane of machined workpiece.

5. CONCLUSIONS

Ultrasonic assistance of microEDM is able to improve all the main technological parameters of the process – surface quality, volumetric relative wear, and machining rate - as our pilot test proved if working parameters are adjusted using optimization conditions based on FEM modelling, even EDM pulses are only randomly overlapped on cumulative microjets phase (*CMP*).

At microEDM+US, the material can be removed in liquid state, the volume being bordered by melting isothermal if EDM pulses are overlapped on *CMP*. Our preliminary experiments pointed that *CMP*, due to very high pressure created of 100 MPa, order of magnitude, can stop the discharge, and consequently collapsing the gas bubble formed around plasma channel. This allows the dielectric liquid to enter EDM spot zone, finding material still in liquid state. Our further technological development will aim at synchronization of µEDM pulses with ultrasonic oscillations. The probability to overlap EDM pulses to *CMP* is relative low, growing at longer pulse times, but it could provide a great reserve of machining rate. At microEDM+US, the material can be removed in solid state too in a greater probability, due to shock waves produced by cavitational effect in the gap that remove peaks of microgeometry, reducing surface roughness.

Several patented solutions were presented regarding microEDM+US. Ultrasonic chains are introduced in equipment constructions in order to assure ultrasonic longitudinal oscillations of electrode-tool, and high pressure of dielectric supply in working gap due to cavitational effect ultrasonically induced. Since the electrode-tool is subjected to deformations affecting precision of micro-machining, the adopted solutions aim at electrode-tool guiding, and precise orientation both of electrode-tool and workpiece.

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