SURFACE ROUGHNESS DECREASE IN THE ELECTROCHEMICAL-ULTRASONIC HYBRID MACHINING

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ABSTRACT: The paper deals with the presentation of a method for numerical modeling and simulation of the effect of the ultrasonic component in the electrochemical-ultrasonic hybrid machining. The focus is on removing surface microgeometry peaks beneath the passivated layer and the surface smoothing mechanism. A shear fatigue resistance calculation was performed for C120 steel. After defining the input parameters, the numerical modeling and simulation were conducted using the specialized software program Comsol Multiphysics. A scanning electron microscope analysis of the processed surfaces was carried out, followed by a study of the influence of each machining parameter (current density, ultrasonic power, machining time).
KEYWORDS: electrochemical machining, ultrasound, roughness, modeling, simulation.

1. INTRODUCTION

The electrochemical-ultrasonic hybrid machining method can be applied to the machining of electrically conductive materials, suitable for complex geometries (such as micro-holes, deep holes, and cavities that cannot be processed by conventional technologies), as well as in various fields (automotive industry, aerospace industry, chemical industry, medical field, MEMS [1], etc.) [2,3].
Electrochemical machining (ECM) is based on the phenomenon of anodic dissolution, where material is selectively removed from the workpiece within an electrolytic cell. In this case, the workpiece acts as the anode, while the tool serves as the cathode [3,4].
Two essential elements that must be understood to realise research in the field of unconventional hybrid technologies are the most commonly used tool materials and the liquid solutions applied in the working area for material removal, to achieve the desired geometry.

Another important aspect related to material characteristics is their electrical resistivity. Tools used for ECM+US machining must be made from electrically conductive and corrosion-resistant materials, considering that material removal is achieved through chemical dissolution.

Density, electrical resistivity, machinability, electrical conductivity, and mechanical strength are important factors regarding the materials used in the manufacturing of tool electrodes.

The application of ultrasonic machining in combination with electrochemical machining leads to a decrease in surface roughness, as the action of ultrasonic cavitation helps remove microgeometry peaks.

The development of counter-pressure chambers could be a trend in electrochemical machining, as it enables control over the flow parameters of electrolyte fluids. This is a critical factor in the material removal mechanism; uneven flow results in uneven removal, which is extremely important in ECM finishing and polishing processes.

In ECM finishing, current densities of 0.05 - 0.5 A/cm² are generally used. Beyond this value, the appearance of gases is observed, followed by overheating and intensified surface attack on the metal, which deteriorates the quality of the processed surface [5,6,10].

It is necessary for J to be uniform in all three of its forms [5,6]:

- ✓ primary current distribution - ohmic;
- ✓ secondary current distribution - kinetic (uniform electrolyte flow);
- ✓ tertiary current distribution - constant concentration in the electrolyte mass (controlled ionic diffusion).

A comparison between electrochemical dimensional machining and electrochemical finishing highlights the following aspects [7,8]:

Material Removal Rate (MRR): In dimensional machining, the focus is on high material removal rates to achieve the desired shape and dimensions, while finishing prioritizes minimal material removal to enhance surface quality.

Surface Quality: Electrochemical finishing aims to achieve superior surface quality with a high level of smoothness and minimal defects. In contrast, dimensional machining may result in a rougher surface, as its primary goal is shaping rather than surface refinement.

Current Density: Dimensional machining typically operates at higher current densities to facilitate faster material removal. Finishing, however, uses lower current densities to avoid excessive surface heating, which could damage the final surface quality.

Electrolyte Flow: Uniform electrolyte flow is crucial in finishing to ensure a consistent, polished surface. In dimensional machining, while electrolyte flow is also important, the requirements are less stringent, focusing more on the rapid evacuation of byproducts.

Precision Requirements: Dimensional machining emphasizes achieving accurate geometric dimensions, with tolerances being more critical. Finishing, on the other hand, emphasizes achieving a specific surface texture and aesthetic quality over precise dimensioning.

On the other hand, in dimensional ECM, the goal is to obtain complex surfaces by removing a larger mass (m) of material. Consequently, the current intensity (I) is high, which implies a high current density (J=I/S). The tool has a shape that is conjugate to the machined surface.

2. MODELING SURFACE ROUGHNESS REDUCTION THROUGH THE EFFECT OF ULTRASONIC CAVITATION

The study was realised in Comsol Multiphysics by sequentially accessing: 2D, Structural Mechanics, Solid Mechanics, Time Dependent.

The following case was studied: modeling the removal of microgeometry peaks from the processed surface, specifically the decrease of roughness, where the loading considered, the pressure exerted by the ultrasonic-induced cavitation is on the order of hundreds of MPa.

The working parameters are presented in figure 1.

Parameters

Name	Expression	Value	Description
hp	5[mm]	0.005 m	part height
lp	10[mm]	0.01 m	part width
Ra	1.6e-6	1.6E-6	roughness before ECM+US
PRa	0.1[mm]	1.0E-4 m	the pitch of micro-irregularities
acr	4e-6	4.0E-6	microdepression radius before ECM+US
bcr	3.6e-6	3.6E-6	microdepression depth before ECM+US
pf	0.5e-6	5.0E-7	passivated film thickness at the top of the microgeometry
tus	64.7e-6	6.47E-5	cavitation bubble implosion time
modulC120	200[GPa]	2.0E11 Pa	Young's modulus C120
nuPC120	0.3	0.3	Poisson's ratio in steel C120
tau0	336	336	breaking strength shear fatigue [MPa] C120
pus	150[MPa]	1.5E8 Pa	cavitation US pressure
modulFe2O3	300[GPa]	3.0E11 Pa	iron oxide Young's modulus
roFe2O3	4345	4345	iron oxide density
nuPFe2O3	0.24	0.24	Poisson's ratio to iron oxide
tau0Fe2O3	57.6	57.6	breaking strength shear fatigue [MPa] iron oxide
Rz	4*Ra	6.4E-6	the maximum height of the micro-irregularities

Figure 1. Working parameters

The shear fatigue strength of C120 steel (τ_0) was determined using the relationship established based on the information from [9]:

$$\tau_0 = 1,2(40+0,16\cdot\sigma_r) \qquad [MPa] \quad (1)$$

$$\tau_0 = 1,2\cdot(40+0,16\cdot 1500) = 336 \text{ MPa}$$

where: σ_r is the static breaking strength of C120 steel; it was assumed that the collective implosion of gas bubbles in the machining working gap, during the phase of cumulative micro-jets occurring at the end of each stretching half-period, represents a fatigue load; the shock waves with a cyclic nature are oriented parallel to the machining working gap and exert shear stress on the micro-peaks of the processed surface.

The parameter τ_0 (tau0 - the shear fatigue strength of C120 material) was analyzed (figure 2) to determine the maximum unit stress up to which the material of the workpiece does not yield.

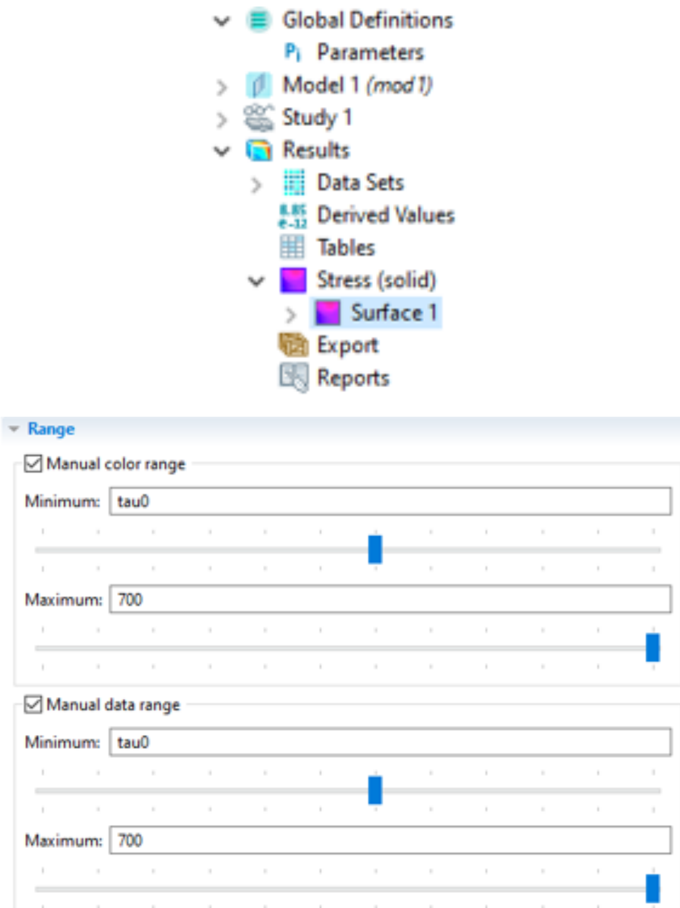

Figure 2. Defining the breaking strength of the workpiece material (C120)

3. THE INFLUENCE OF ULTRASONIC CAVITATIONAL PRESSURE VARIATION ON SURFACE QUALITY

In figure 3 are presented the areas of material removed from both the peaks of the micro-geometry and the sidewalls of the crater resulting from ECM+US machining.

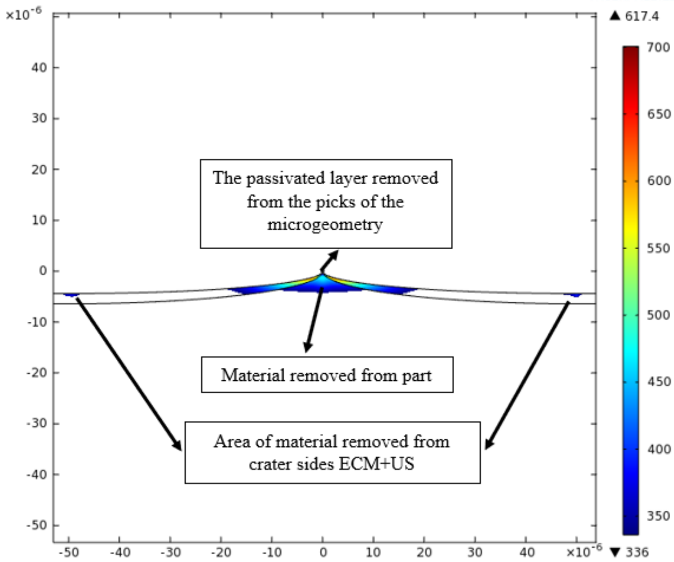

Figure 3. Definition of the material removal zones

After applying cavitational ultrasonic pressure to achieve uniform roughness reduction, the goal is for the material removed from the workpiece not to fall below the level of the initial microdepressions present before ECM+US machining.

Table 1 presents data obtained from COMSOL Multiphysics and the roughness values corresponding to cavitational ultrasonic pressure.

Table 1. Roughness decrease data

pus [MPa]	h_2 [µm]
110	1.7573
120	2.5024
130	3.0843
140	3.6645
150	4.2456
160	4.7731
170	5.2197
180	5.7216
190	6.2075
200	6.5404
210	6.8832
220	7.3247

where h_2 is the depth of the removed layer [µm].

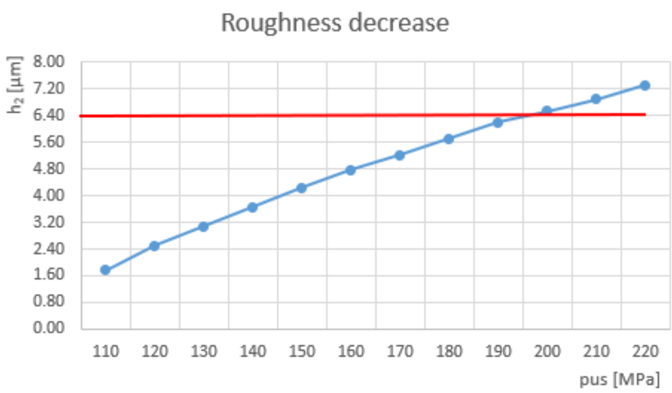

Figure 4. The influence of cavitational ultrasonic pressure on roughness decrease

From the data in the graphical representation in figure 4, it can be observed that there is an optimal value for the cavitation ultrasonic pressure, pus = 195 MPa, which allows for the minimization of the roughness of the processed surface. This corresponds to an optimal power consumption in the ultrasonic chain, which determines the amplitude (A) of the ultrasonic vibration.

The ultrasonic pressure pus can be theoretically determined using the relationship [11]:

$$p_{US} = 2\pi \cdot f_{US} \cdot A \cdot \rho \cdot c_S \quad [Pa] \quad (1)$$

where: f_{US} is the ultrasonic oscillation frequency of the electrode in the longitudinal direction [Hz];

A is the amplitude of the oscillations [m];

ρ is the density of the working fluid [kg/m³];

c_S is the speed of sound in the electrolyte solution [m/s].

Relation (1) indicated that the ultrasonic pressure pus can be increased by growing the amplitude A, which is possible by increasing the consumed ultrasonic power Pcus on ultrasonic chain - working parameter at ECM+US hybrid machining.

The optimal power value of pus will be determined experimentally.

4. THE ANALYSIS OF ELECTRON SCANNING OF MACHINED SURFACES

A scanning electron microscope, SEM QUANTA INSPECT F50, was used to realise the morphological structure of the machined surfaces based on the machining parameters used.

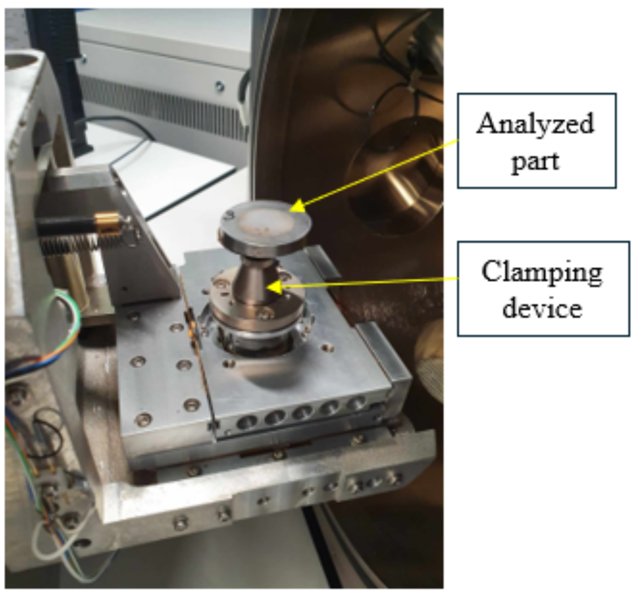

Figure 5. Positioning of the testing part

Applications of the SEM QUANTA INSPECT F50 scanning electron microscope:

- microstructural and microcompositional analysis of metallic, ceramic, composite materials, powders, and thin films;

- qualitative and quantitative X-ray microanalysis;

- visualization, characterization, and dimensional measurement of nanostructured samples.

Figure 5 shows the positioning of the sample inside the scanning electron microscope chamber.

Synthesis of the information obtained through SEM scanning of the C120 testing parts:

The study conducted with the SEM QUANTA INSPECT F50 scanning electron microscope indicates that the samples are made from a tool steel of the ledeburitic class, characterized by a high density of both primary and secondary carbides.

The primary carbides are large and have polyhedral shapes. The rounded particles in a network formation may be carbides precipitated during heat treatments, which have a strong hardening effect.

A successive electrochemical-ultrasonic machining method was established as follows [11]:

- supplying the ECM cell with a 5% NaCl electrolyte;
- 30-second pause time;
- ultrasonic machining for 1 minute and 30 seconds;
- starting electrolyte flushing for 30 seconds;
- 30-second pause time;
- electrochemical machining for 1 minute and 30 seconds;
- repeating the cycle three times.

Data provided by the SEM (figures 6-7) is presented for a series of test samples finished using successive electrochemical-ultrasonic machining, (with current density J maintained and power consumption on the ultrasonic chain increased), with the machining parameters shown in table 1.

The current density was kept constant, and the influence of the ultrasonic power consumed in the ultrasonic chain was studied.

In figure 7, at a medium current density, lighter-colored Cr and W carbide particles can be observed. At lower ultrasonic power levels PcUS, microcavities have formed, likely due to the varied removal of these constituents, which have different fatigue resistance characteristics, as previously demonstrated in the modeling and numerical simulation of the ECM+US process.

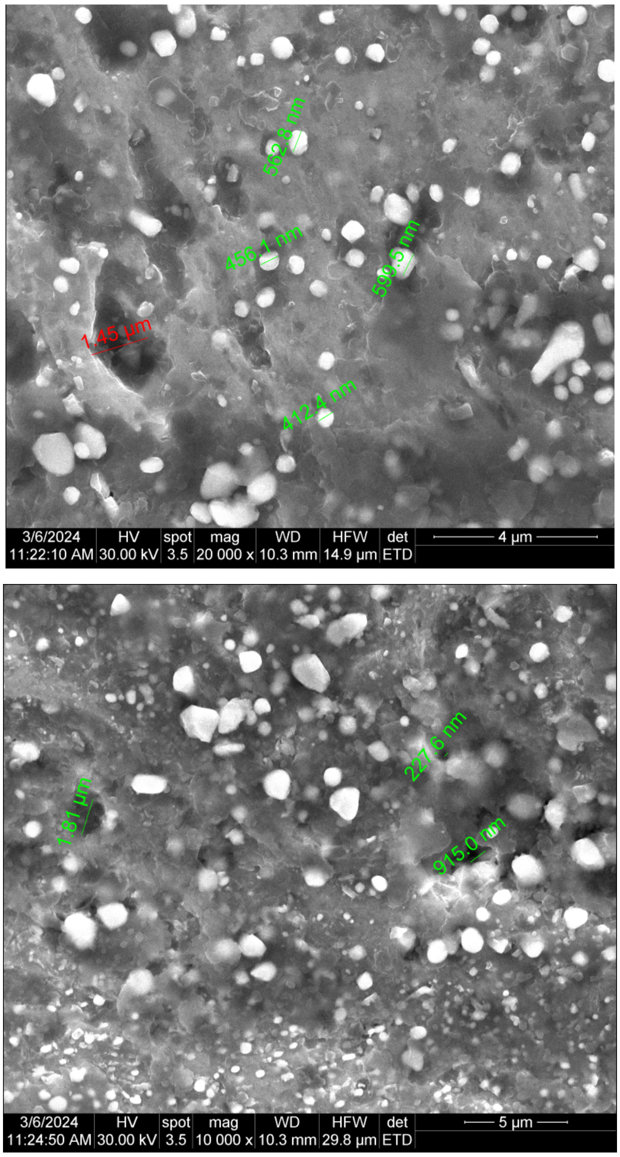

Figure 6. SEM images of the surfaces of a C120 test sample, machined through successive ECM+US [11]

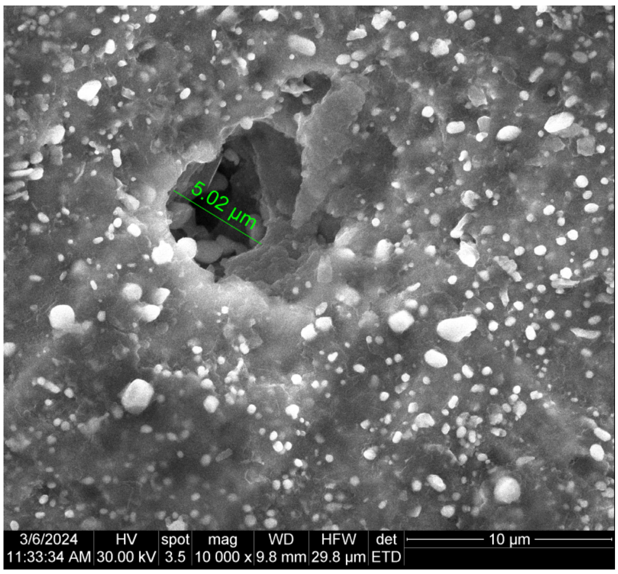

Figure 7. SEM images of the surfaces of a C120 test sample, machined through successive ECM+US_increasing PcUS [11]

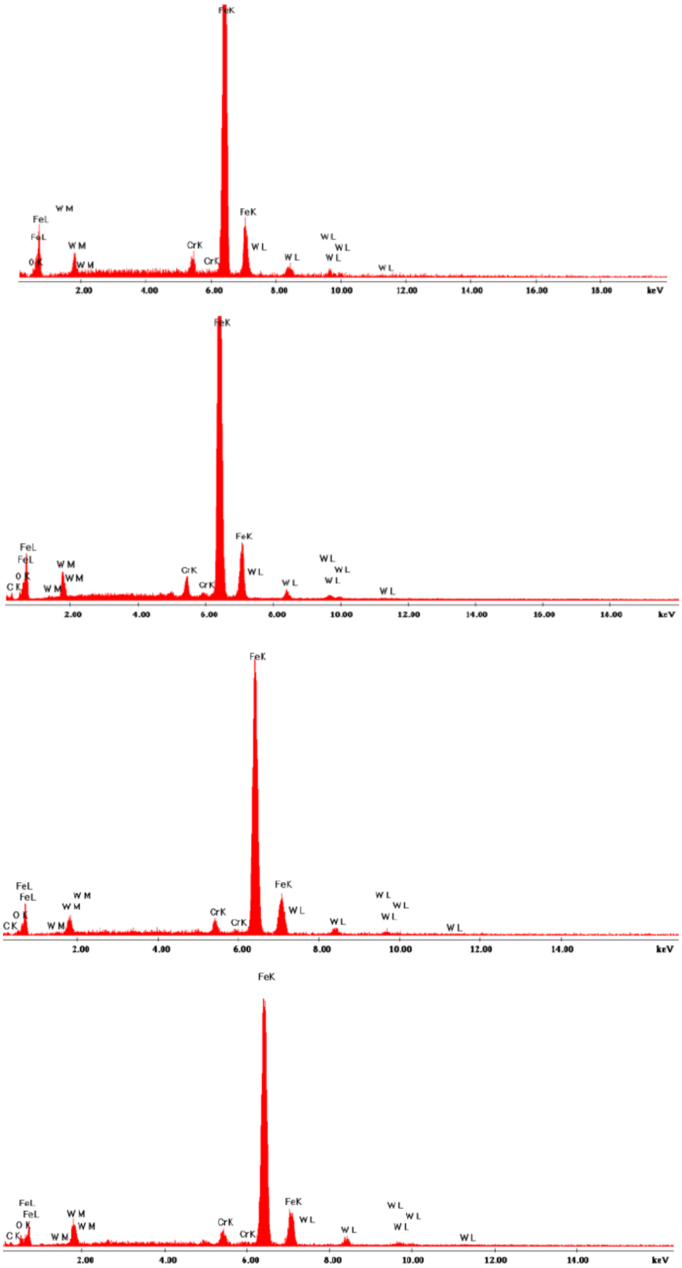

Figure 8. Graphical representation of the percentage of the constituent elements of the base material for the C120 testing parts

With the further increase in the ultrasonic power consumed in the ultrasonic chain, PcUS, as shown in figure 7, an improvement in roughness occurs, but microdepressions of micrometer dimensions are also accidentally produced.

An EDAX (an energy-dispersive X-ray detector) investigation was performed on the machined testing parts to determine their percentage chemical composition.

The analysis was performed on the testing parts finished through successive electrochemical-ultrasonic machining.

Figure 8 presents the graphical representation of the percentage of the constituent elements of the base material for the C120 steel test parts.

5. RESULTS OF THE HYBRID ELECTROCHEMICAL-ULTRASONIC MACHINING

Hybrid electrochemical-ultrasonic machining was applied for finishing C120 testing parts, and the results are presented in table 2.

It was realised a successive machining, first was applied the ultrasonic machining and then the electrochemical machining for a number of five parts.

The influence of ultrasonic power on the roughness of the machined surface:

Table 1. Working parameters successive ECM+US, C120

	PcUS [W]	J [A/cm^2]	s_F [mm]	Initial Ra [µm]	Ra ECM+US [µm]	Roughness decrease Ra ECM+US [%]
1	94.8	0.306	0.7	0.916	0.84	8.297
2	103.2			0.488	0.341	30.123
3	109.2			0.636	0.419	34.119
4	114			0.808	0.65	19.554
5	118.8			0.863	0.77	10.776

Figure 9 shows the variation of the percentage decrease in roughness in relation to the ultrasonic power consumed.

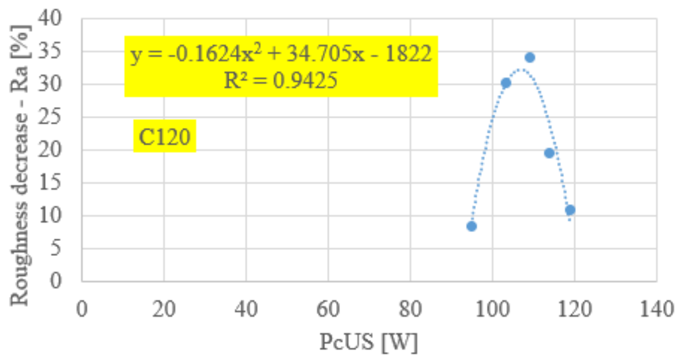

Figure 9. Influence of the ultrasonic power consumed

The optimization of the power consumed in the ultrasonic chain was pursued, resulting in a maximum percentage reduction of surface roughness Ra of 34% at PcUS = 109.2 W. It is noted that a front gap value s_F = 0.7 mm allows for the evacuation of the products resulting from the hybrid ECM+US finishing process, as the increased hydraulic resistance in the front gap s_F creates better flow conditions for the electrolyte.

The influence of current density on the surface roughness of the machined surface in successive ECM+US finishing of testing parts made from C120:

The current density was varied for the electrochemical-ultrasonic finishing of testing parts made from C120 (table 2), at an ultrasonic power value of PcUS = 118.8 W.

Table 2. Working parameters successive ECM+US, C120

	J [A/cm²]	PcUS [W]	SF [mm]	Ra inițial [µm]	Ra ECM+US [µm]	Reducere Ra ECM+US [%]
1	0.102	118.8	0.3	0.679	0.57	16.053
2	0.153			0.433	0.325	24.942
3	0.204			0.538	0.39	27.509
4	0.306			0.764	0.6	21.466
5	0.408			1.4	1.26	10.000

Figure 10 shows the percentage variation in the reduction of roughness Ra as a function of current density.

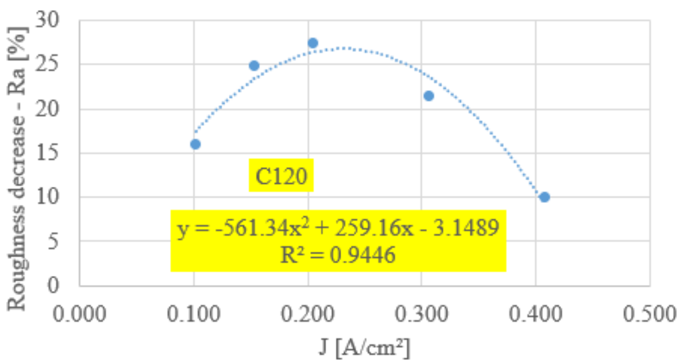

Figure 10. Influence of current density

An improvement in the percentage decrease of roughness is observed in the range J = 0.153-0.306 A/cm^2, with the maximum reduction of approximately 27% occurring at J = 0.204 A/cm^2. Thus, the optimization of the current density J was achieved, with the objective function being the percentage decrease of the roughness Ra of the machined surface.

6. CONCLUSIONS

The hybrid machining method, electrochemical-ultrasonic, contributes to decreasing the roughness of the processed surface through both components: anodic dissolution begins at the peaks of the microgeometry where the electric field is more intense (there is a critical time after which the obtained roughness increases); the cavitation induced ultrasonically in the working gap primarily removes the peaks of the microgeometry (there is an optimal power value consumed in the ultrasonic chain, beyond which higher powers lead to increased roughness).

Future articles will present additional results from the application of hybrid electrochemical-ultrasonic machining technology, technical aspects related to the equipment used and developed, as well as ways to prevent potential disadvantages.

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