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DOCTORAL THESIS

RESEARCH ON HYBRID ELECTROCHEMICAL-ULTRASONIC FINISHING PROCESSING

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Keywords: electrochemical-ultrasonic processing, hybrid, simulation, modeling, simultaneous, successive.

CHAPTER 1.
TYPES OF HYBRID UNCONVENTIONAL PROCESSES

1.1 Classification of simple and hybrid non-conventional technologies

According to the specialized literature, non-conventional technologies (TN) can remove the material from the surfaces of the parts, at the micrometric or nanometric level, applying various types of energy. These technologies process parts through a concentrated transfer of energy, from the tool to the semi-finished product, and in general, there is no contact between the tool and the part, the distance between them being called the working gap, its values being very small, usually in most cases processing being up to a maximum of 1 mm [1.85].

Starting from the technologies mentioned in the tables above, hybrid processing procedures can be developed, two or more of them being combined, which can be applied **simultaneously** or **successively**. Hybrid machining means the combination of processes to take material in a more efficient and productive way.

A general objective of hybrid manufacturing is the “1 + 1 = 3” effect [185], which means that the positive effect of the hybrid process is the amplification of the effects of the individual processes [138,139].

In the literature, in the field of non-conventional technologies, several interpretations of the term hybrid can be identified as follows [5,187]:

- combination of different active energy sources acting at the same time in the processing area;
- processes that combine steps usually performed in two or more phases (successive).

Also, hybrid manufacturing processes can be grouped into two major categories [5,137]:

A) combined or mixed processes where all constituent processes are directly involved in material removal;

B) assisted type processes in which only one of the participating processes directly removes the material, while the other has a positive effect on the processing conditions.

Through the prism of this classification, the electrochemical hybrid finishing processing in the ultrasonic field falls into the category of combined or mixed technology, since both the electrochemical and the ultrasonic components sample the material, with different weights: the first by anodic dissolution and the second by mechano-hydraulic sampling.

1.2 Unconventional Hybrid Vibration Machining

Following an analysis regarding the application of vibrations in the field of non-conventional technologies, in the following, some theoretical aspects will be presented, as well as the main principle schemes developed in specialized literature, regarding the application of vibrations on the elements of the work environment (workpiece, tool-electrode or the working fluid).

1.3 Unconventional Hybrid Laser Machining

Laser processing (Laser Beam Machining - LBM) of various metallic or non-metallic materials constitutes energetic applications that include: cutting, drilling, welding, marking and inscription, etc. The laser is also used to perform a wide range of thermal and thermochemical treatments.

The wide applicability of LBM is justified by the fact that the laser creates one of the highest power densities (radiation intensity) in the technological field and recently, we are witnessing a reduction in the costs of these installations.

A numerical simulation of hybrid laser technology - EDM in a successive approach is presented in a paper developed by the researchers Marinescu N., Ghiculescu D., respectively Nanu S. [157].

1.4 Fluid Assisted Hybrid Unconventional Machining

- **Ultrasonic processing assisted by electrorheological fluids**

One of the solutions to restrict the generation of defects is the use of electrorheological fluid (fluid that can change its viscosity by the action of an external electric field). As the intensity of the electric field increases, the viscosity of the fluid increases. Silicon oil and dielectric form the ingredients of an electrorheological fluid. In the absence of an electric field, the dielectric particles remain dispersed in the silicon oil. The attractive force between the dielectric particles produces an increased viscosity of the electrorheological fluid.

1.5 Magnetic Field Assisted Hybrid Unconventional Processing

Accumulation of particles in the machining area that adversely affects process performance and efficiency has always been a problem for EDM. The introduction of the magnetic field exerts a force perpendicular to the movement of the electrode. As a result, the material particles are subject to both a magnetic force and a centrifugal force.

The EDM process with magnetic activation with results regarding the increase of its productivity and stability is also described in the works carried out by researchers such as A. M. Șițu, respectively D. Nanu, L. Slătineanu, D. Ghiculescu, and other collaborators in a treatise on unconventional technologies [158,159].

1.6 Other types of non-conventional hybrid processing

- **Electrochemical Reactions and Electrical Discharge Processing (ECDM)**

Methods of processing hard metals, which are difficult to machine with conventional methods, continue to attract attention. Electrochemical machining and EDM have been combined in a hybrid process, ECDM.

1.7 Conclusions

- Hybrid machining processes are in the developmental phase of the life cycle, and some are even emerging, leaving ample scope for future investigation. Process mechanisms, simulation methods, ultra-precision machine tools for hybrid micromachining, process monitoring and metrology techniques, cost efficiency and industrial implementation are elements to be explored.

CHAPTER 2.
ULTRASONIC CHAINS FOR UNCONVENTIONAL HYBRID PROCESSES

2.1 Structure of ultrasonic chains

Ultrasonic systems are known to produce and transmit ultrasonic oscillations. The frequency range of ultrasound is considered to be greater than 20 kHz reaching up to 1 GHz [2].

Next, in this chapter, all the component elements of a technological process using ultrasound will be described in a general way.

2.2 Assembly methods

When assembling piezoceramic transducers, special attention must be paid to the method of joining the piezoceramic elements with the radiating surface, which can be done by hard soldering, welding or screws (the most used).

Assembling the concentrator with the vibration generator, in order to make up the transducer assembly, can be done either by gluing or by threading.

The creation of ultrasonic concentrators, which integrate the tool, requires obtaining the resonance condition (with high time consumption). The natural frequency of the transducer is considered the target frequency, its value is given by the supplier. In the case of applications, hybrid technologies that use ultrasound, the technologist's task is to superimpose the frequency of the concentrator, which integrates the tool, over the frequency of the transducer. This is facilitated by hub modeling and simulation. Finally, the resonance frequency is obtained by minimal adjustments of the concentrator dimensions.

2.3 Conclusions

- The structure of the ultrasonic chain must be well defined and known, and the ultrasonic generator, power source, ultrasonic transducer need to be adjusted to transmit the desired frequency or current intensity established by calculations.

CHAPTER 3.
ANALYSIS OF THE OPERATION OF ULTRASONIC CHAINS

3.1 Ultrasonic chain sizes and natural frequencies

Several types of ultrasonic waves can propagate in solid media, they differ by [2]: the shape and direction of the trajectories they transmit to the particles of the material in which they are propagated, the speed of propagation, the distance at which they are likely to propagate in material.

To achieve the resonance condition, it is necessary to determine the natural frequency of the US chains, which is facilitated by numerical modeling and simulation with finite elements, prior to the physical realization.

3.2 Types of ultrasonic waves

There are four types of ultrasonic waves: longitudinal or compressive waves, transverse or shear waves, surface or RAYLEIGH waves, and LAMB or plate waves.

3.3 Parameters of ultrasonic waves

The parameters of ultrasonic oscillations are: period, frequency, amplitude of oscillation, etc. (according to table 3.1 of the complete thesis).

3.4 Ultrasonic chains integrated in processing equipment

In addition to the spectacular improvement of the technological parameters of the ultrasonic EDM (EDM+US) compared to the classical EDM technology, however, the EDM+US technology has an important disadvantage caused by the lack of flexibility. This is derived from the critical technological condition that must be met when the ultrasonic chain operates at resonance, which implies equality between the natural frequencies of the main components of the ultrasonic chain, the ultrasonic transducer and the ultrasonic concentrator, which also includes the tool electrode as an integral part or the like , the workpiece [2].

3.5 Conclusions

There is a growing trend to use ultrasonic vibrations in various conventional or non-conventional processes with the aim of improving the previously presented technological parameters at low costs. The hybridization of classic technologies represents an essential element in the development of new non-conventional technologies and also an important step for Industry 4.0 through their ability to concentrate energy on very small spaces.

CHAPTER 4.
ANALYSIS OF HYBRID, ELECTROCHEMICAL-ULTRASONIC PROCESSING

4.1 Usual electrochemical processing

The electrochemical machining (Electrochemical Machining - ECM) of a surface takes place in an electrolytic cell, and the phenomenon underlying it is anodic dissolution and the contralateral sampling of the electrically conductive material. In the case of this processing, the tool represents the cathode, and the surface to be processed the anode, these being immersed in an electrolytic solution of base, acid or salt type.

4.2 Depassivation methods

There are several depassivation methods: chemical depassivation, electrical depassivation, mechanical depassivation, hydrodynamic depassivation, hybrid depassivation.

4.3 Hybrid electrochemical-ultrasonic processing

The hybrid process of electrochemical-ultrasonic processing can be applied to the processing of electrically conductive materials, for complex geometries (micro-holes, deep holes, cavities that cannot be processed by conventional technologies), but also various fields (automotive industry, aerospace industry, chemical, medical, MEMS [169], etc.) [2,166].

4.4 Phenomenon specific to electrochemical processing combined with ultrasound

In the processing interstitium, the phenomena are based on the laws of electrolysis [170], considering the low interelectrode voltage (less than 24 V). Following the chemical reactions, a passivated (electrically neutral) layer appears, which needs to be removed.

4.5 Back pressure chambers

Back pressure chambers are elements used to keep the pressure and flow rate under control in the work area.

4.6 Advantages and disadvantages of electrochemical machining combined with ultrasound

All processing technologies, both conventional and non-conventional, present a series of advantages and disadvantages respectively. For electrochemical technology combined with ultrasound, they are presented in table 4.4, detailed in the thesis [2,85].

4.7 Conclusions

In the case of hybrid electrochemical-ultrasonic processing, the removal of the passivated layer can be achieved with the help of ultrasound, having the advantage of lower pressures of the electrolytic liquid.

CHAPTER 5.
OBJECTIVES, RESEARCH DIRECTIONS AND METHODOLOGY ADDRESSED IN THE DOCTORAL THESIS

5.1 Synthesis of critical issues regarding the current status of unconventional hybrid technologies

From the critical analysis of the current state of non-conventional hybrid technologies, certain conclusions were developed that facilitated the formulation of objectives and research directions within the thesis.

5.2 The objectives of the doctoral thesis

From the critical analysis of the current state, the main objective of the thesis and subordinate secondary objectives emerged, formulated in a chronological and gradual sequence.

The main objective of the doctoral thesis is the following:

Design, operation simulation, realization and experimentation of an electrochemical-ultrasonic hybrid finishing equipment (ECM+US)

When achieving the main objective, the transition from the concept level, technological maturity level TRL 2 (technology readiness level), to that of TRL 4 [162,163,164], functional model, **hybrid electrochemical - ultrasonic finishing equipment (ECM+US)** was followed under laboratory conditions.

Thus, several specific objectives were established, subordinated to the main objective, as follows:

Os1: Formulation of ECM+US hybrid finisher functions, primary and secondary, and its corresponding structure.

Os2: Development of a working circuit / operation of the electrochemical-ultrasonic hybrid finishing equipment, taking into account all the necessary components: back pressure chamber or electrochemical cell, power source, ultrasound generator, electrolytic liquid tank with filter elements, pump of liquid transfer.

Os3: Establishing the shape and dimensions of the ultrasonic chain in accordance with the resonance frequency - target by modeling and numerical simulation.

Os4: Analysis of the application by modeling and numerical simulation of different polymeric materials on the surface of the concentrator for electrical isolation and avoiding accidental electrochemical processing.

Os5: Detailed Design of Simple and Hybrid Electrochemical - Ultrasonic Finishing Equipment.

Os6: Realization of ECM+US hybrid finishing equipment.

Os7: ECM+US hybrid finishing equipment testing.

Os8: Identification of non-conformities and their possible causes in the design, manufacture and testing in laboratory conditions of the finishing equipment ECM+US-TRL 4.

Os9: Establishing optimal processing regimes, taking into account several working parameters, in ECM+US hybrid finishing under laboratory conditions - TRL 4.

5.3 Research directions and research methodology within the doctoral thesis

The major research directions to be pursued in the PhD thesis, as foreshadowed after the critical analysis of the current state of unconventional hybrid technologies in general and the hybrid electrochemical-ultrasonic finishing machining (ECM+US) technology.

CHAPTER 6.
CONCEPTUAL DESIGN OF ELECTROCHEMICAL-ULTRASONIC HYBRID FINISHING EQUIPMENT

6.1 General data

Starting from the need expressed by this doctoral thesis, the development of an electrochemical-ultrasonic processing equipment, taking into account the stages of the conceptual design process, the general function was defined, after which the main and secondary functions were also developed.

6.2 Formulation of the functions of the electrochemical-ultrasonic finishing equipment

The processing equipment, the design and development of which is one of the objectives of the doctoral thesis, has as its **general function** the finishing of the surfaces of the parts through the hybrid technology, electrochemical processing combined with ultrasound.

6.3 Establishing the structure of the main functions

The structure of each main function is elaborated within the thesis according to table 6.3.

6.4 Identifying solutions

In the framework of the thesis, table 6.4 specifies the solutions chosen for each main function separately.

In this chapter, the secondary objective, Os1: Formulate the functions of the ECM+US hybrid finishing equipment, primary and secondary, and its corresponding structure, was fulfilled.

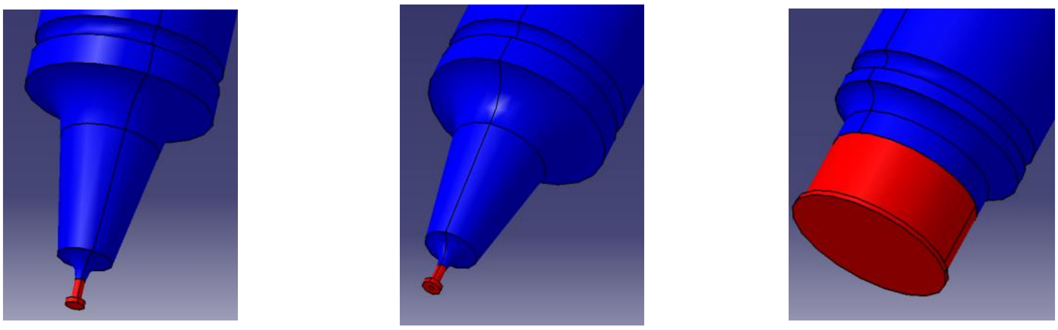
6.5 Conclusions

- The stages of conceptual design of an electrochemical-ultrasonic processing equipment were defined, by formulating the main and secondary functions and establishing their structure, after the general function was presented.

CHAPTER 7.
MODELING, NUMERICAL SIMULATION OF THE OPERATION OF ULTRASONIC CHAINS USED IN THE HYBRID FINISHING PROCESS, ELECTROCHEMICAL - ULTRASONIC PROCESSING

7.1 Radiant bush selection and concentrator sizing

Applying the computational principles and relationships mentioned in the thesis, five concentrator models (figure 7.2) with different geometrical and shape characteristics were developed to see how they behave in terms of resonant frequency.



US chain with conical horn, ø4 mm

US chain with tapered horn, ø4mm with a ø1x0.5mm hole

US chain with stepped cylindrical concentrator, ø32 mm

US chain with stepped cylindrical horn, ø32mm with a ø4x2mm hole

US chain with stepped cylindrical concentrator - ø25 mm copper tool-electrode

Fig. 7.2 Active surfaces of designed, modeled US chains

7.2 Finite element modeling of the operation of various variants of concentrators and integrated tools

At this stage, several forms of concentrators (Figures 7.17, 7.19, 7.31, 7.33, 7.36, 7.37, 7.40) were modeled with tools of various integrated shapes.

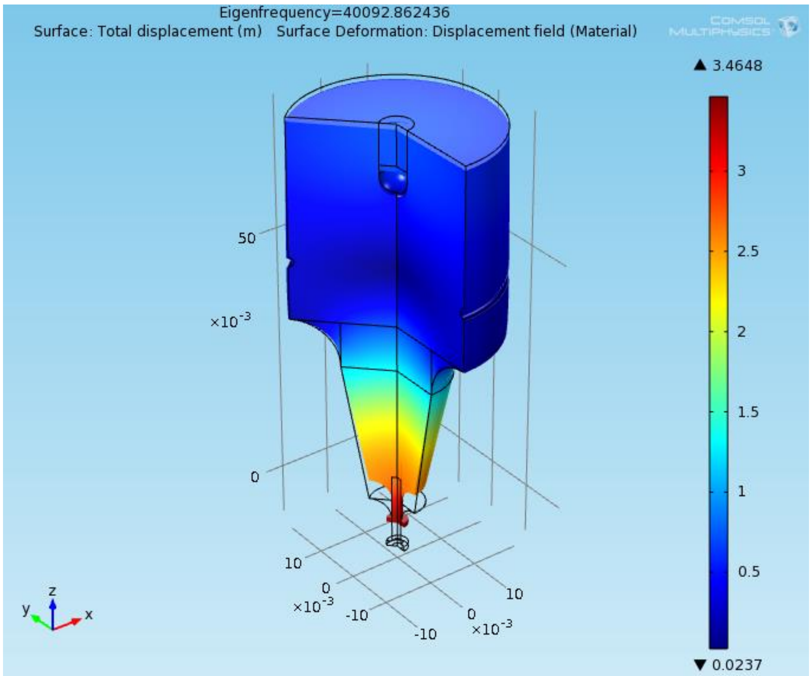


Fig. 7.17 3D model of the concentrator with deformations during US vibrations - Model 1

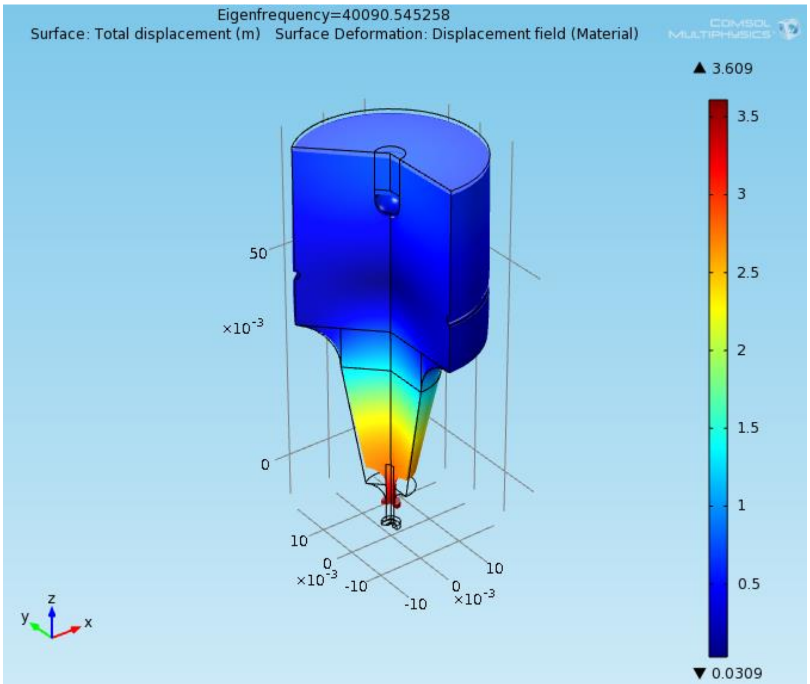


Fig. 7.19 3D model of the concentrator with deformations during US vibrations - Model 2

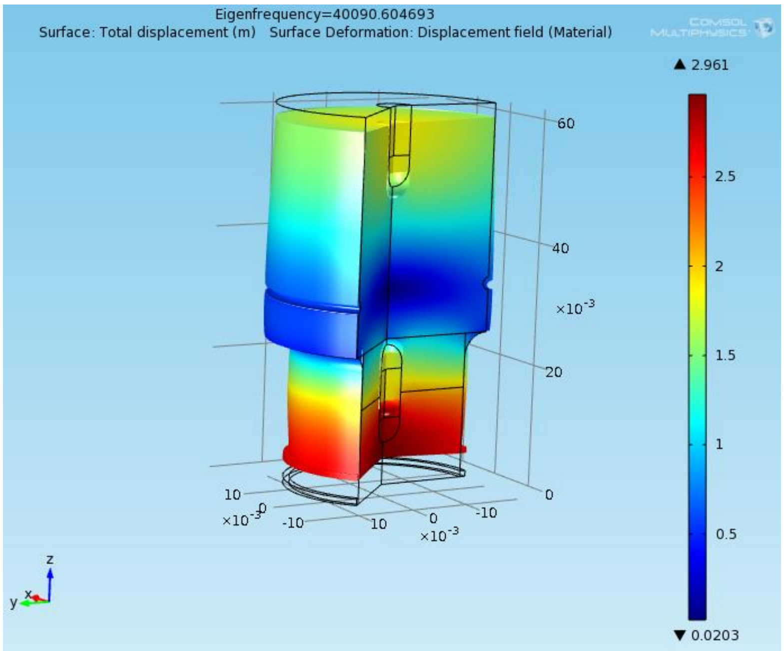


Fig. 7.31 3D model of the concentrator with deformations during US vibrations - Model 3, Target frequency = 40 kHz

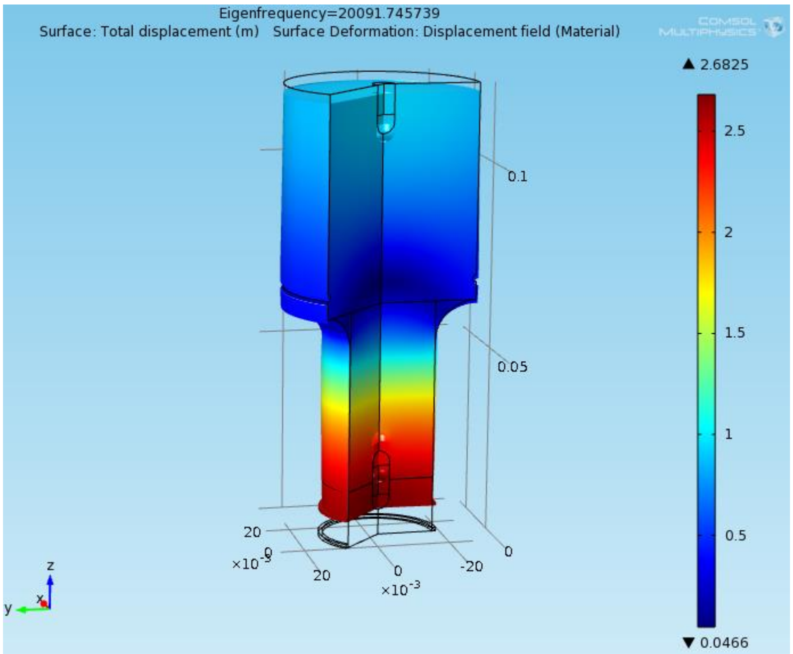


Fig. 7.33 3D model of the concentrator with deformations during US vibrations - Model 3, Target frequency = 20 kHz

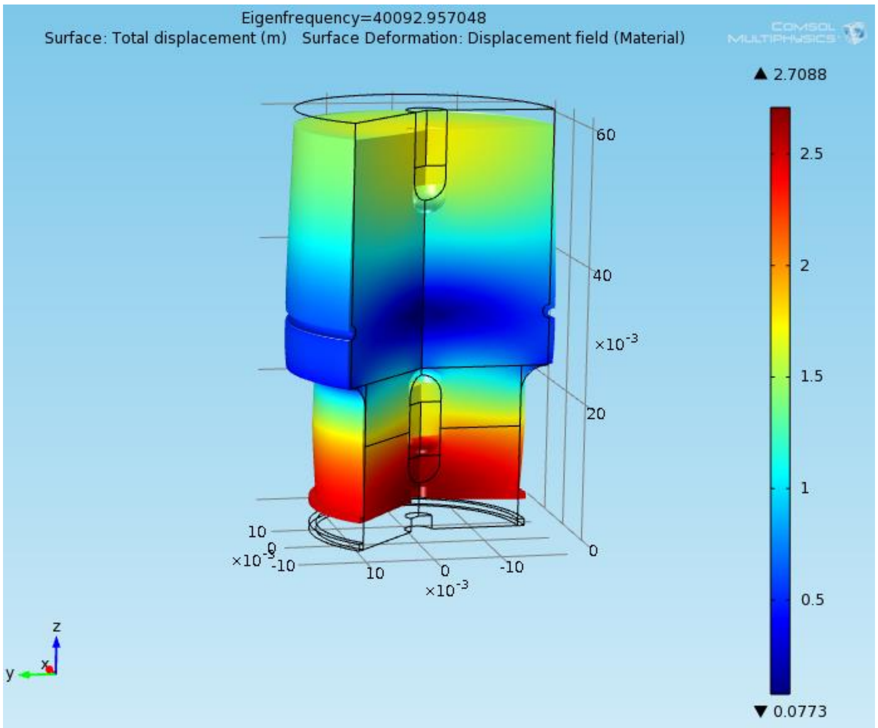


Fig. 7.36 3D concentrator model with deformations during US vibrations - Model 4, Target frequency = 40 kHz

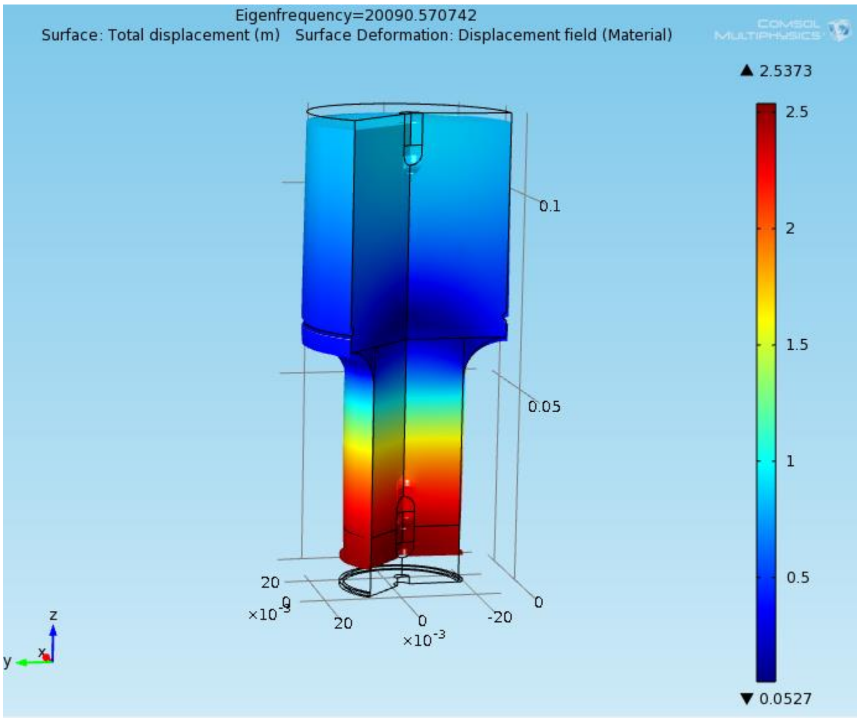


Fig. 7.37 3D model of the concentrator with deformations during US vibrations - Model 4, Target frequency = 20 kHz

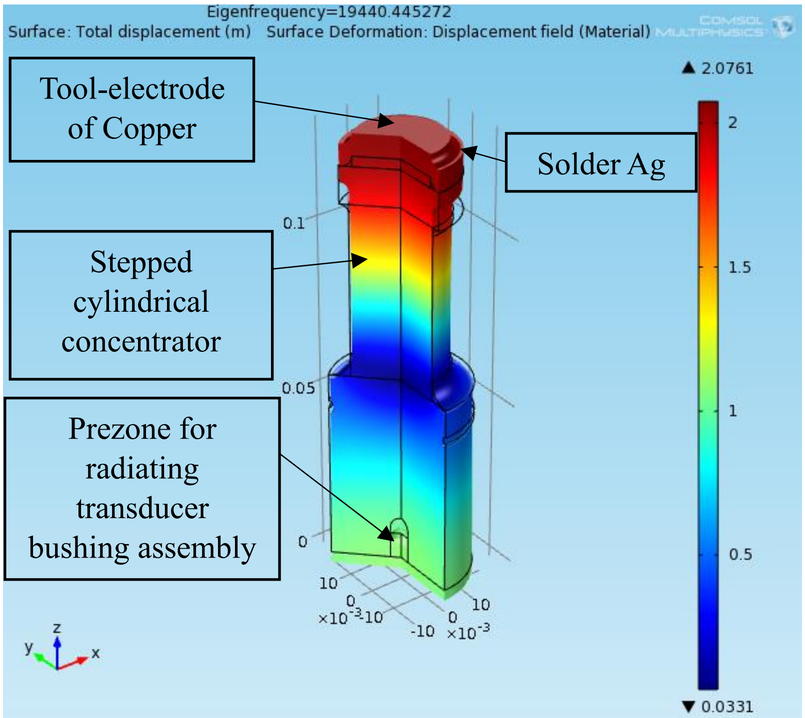


Fig. 7.40 3D concentrator model with deformations during US vibrations - Model 5, Target frequency = 19440 Hz

7.3 Amplification and elongation variation plots

Following an analysis carried out in the Comsol program, the necessary data were extracted to create variation graphs of amplification and elongation.

In the nodal plane, determined according to the previously presented methodology, a circular channel with a radius of 1 mm is practiced, which serves to fasten the US chain with radial screws, which are assembled in the nodal flange.

7.4 Conclusions

Analyzing the results of concentrator modeling and numerical simulation of their operation, some conclusions were formulated, fully presented in the thesis:

- For hybrid electrochemical-ultrasonic finishing, was chosen the concentrator that has the tool electrode of copper being soldered with Ag, considering the zero tool wear at the ECM.

Objective Os3 was accomplished: Establishing the shape and dimensions of the ultrasonic chain used in the design of the experimental model of hybrid, electrochemical-ultrasonic finishing and further in its testing.

CHAPTER 8.
NUMERICAL MODELING AND SIMULATION OF THE INFLUENCE OF INSULATING MATERIALS ON ULTRASONIC CHAIN CHARACTERISTICS

8.1 Influence of polyvinyl chloride

According to the work scheme, results after the conceptual design, the hybrid electrochemical-ultrasonic finishing of the US concentrator, with the tool-electrode at the end, is immersed in the electrolytic liquid. Since the materials from which these two elements of the technological system are made are electrically conductive, they must be isolated to prevent their accidental processing, because during the ECM+US finishing process, an electric field is created between the processed surface (connected to the anode) and the mentioned elements (connected to the cathode).

The application area of the PVC layer is presented in figure 8.3.

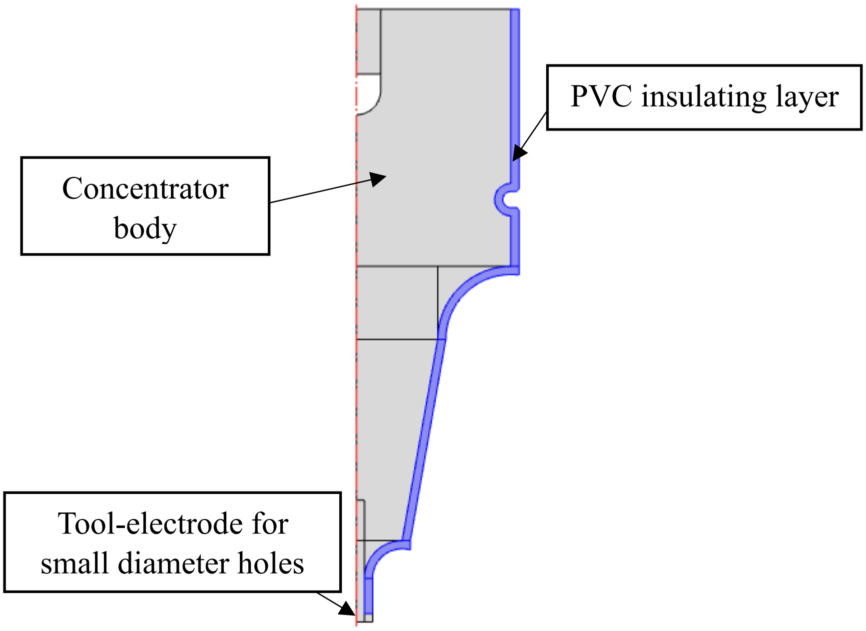


Fig. 8.3 The application area of the PVC layer

8.2 The influence of polyamide

Another material that can be used as an electrical insulation element is polyamide.

In the case of adding the polyamide layer, for the first two models there is a decrease in frequency by 780 Hz and 634 Hz, respectively. In contrast, for the other two the drop is around 288-289 Hz.

8.3 The influence of polyethylene

The third material applied to the assembly, whose influence on the natural frequency of the concentrator was analyzed in the Comsol program, is polyethylene.

In the case of polyethylene, the values show a decrease in frequency by 690 Hz and 696 Hz, respectively, for the first two models, and for models three and four, the decrease is 266-268 Hz.

8.4 Influence of epoxy paint

Epoxy paint or resin is considered useful for protecting the component elements of an ultrasonic chain (figure 8.9), being easier to apply than the other materials, that is why its analysis was carried out in Comsol.

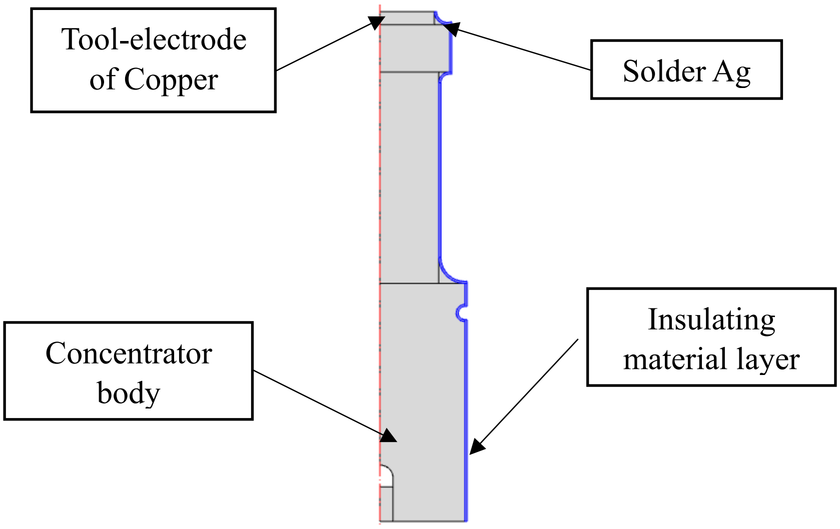


Fig. 8.9 Application of the layer of insulating material

8.5 Conclusions

- The application of polyvinyl chloride (PVC) results in a considerable frequency drop of approximately 1235 Hz for the conical concentrator designs and 472 Hz for the stepped cylindrical concentrator designs with a target natural frequency of 40100 Hz and a drop of 215 Hz for those operating at a target natural frequency of 20100 Hz, the calculations being made at an insulating layer thickness value of 1 mm.

Secondary objective Os4 was achieved: Analysis of the application by modeling and numerical simulation of different polymeric materials on the concentrator surface for electrical isolation and avoidance of accidental electrochemical processing.

CHAPTER 9.
NUMERICAL SIMULATION OF SOME COMPONENTS OF THE ELECTROCHEMICAL-ULTRASONIC HYBRID FINISHING PROCESS

9.1 Technological solutions for depassivation

Several solutions are presented for removing the neutral, passivated layer that forms on the ECM machined surface.

9.2 Numerical simulation of the effect of the ultrasonic component in the hybrid electrochemical-ultrasonic machining process

This stage focuses on modeling and numerical simulation of the effect of the ultrasonic component in the hybrid electrochemical-ultrasonic machining process.

Starting from the analysis of the formation mechanism of the passivated layer on the processed surface of a C120 steel (with main elements, 2% C and 12% Cr), two phenomenon were considered:

- ultrasonic depassivation, specific to the ECM+US hybrid process, namely the removal of the passivated layer of iron oxide through the action of ultrasonic cavitation induced in the processing gap;
- removing the peaks of the microgeometry of the machined surface from under the passivated layer, respectively the surface smoothing mechanism.

9.2.1 Numerical simulation of ultrasonic depassivation

Figures 9.16-9.19 show the variations of the areas from which the material layer is removed and the arrangement of the passivated layer according to the applied cavitational ultrasonic pressure.

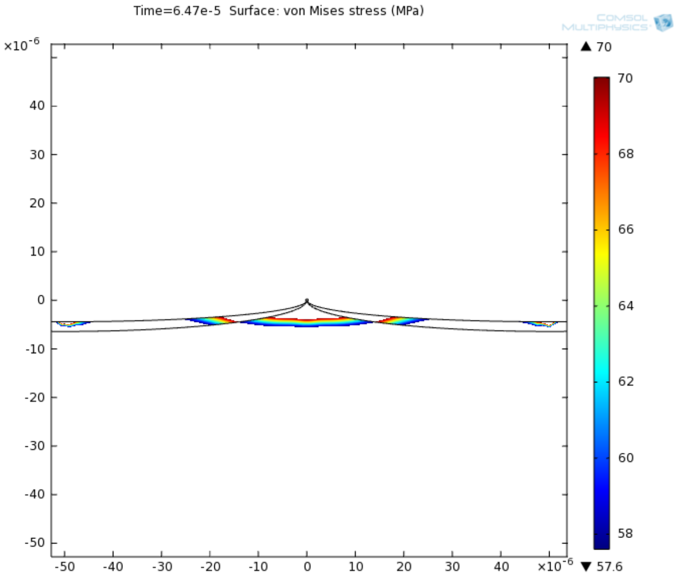


Fig. 9.16 Disposition of the passivated layer and the layer of sampled material, US pressure = 30 MPa

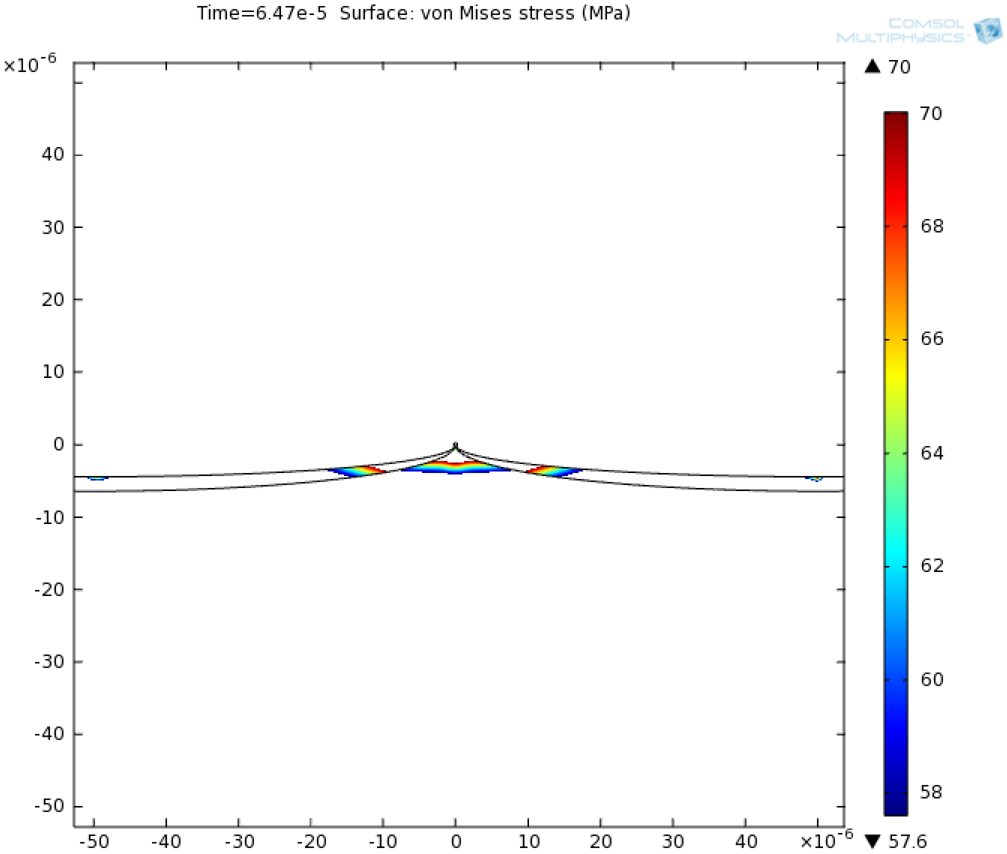


Fig. 9.17 The arrangement of the passivated layer and the layer of sampled material, US pressure = 25 MPa

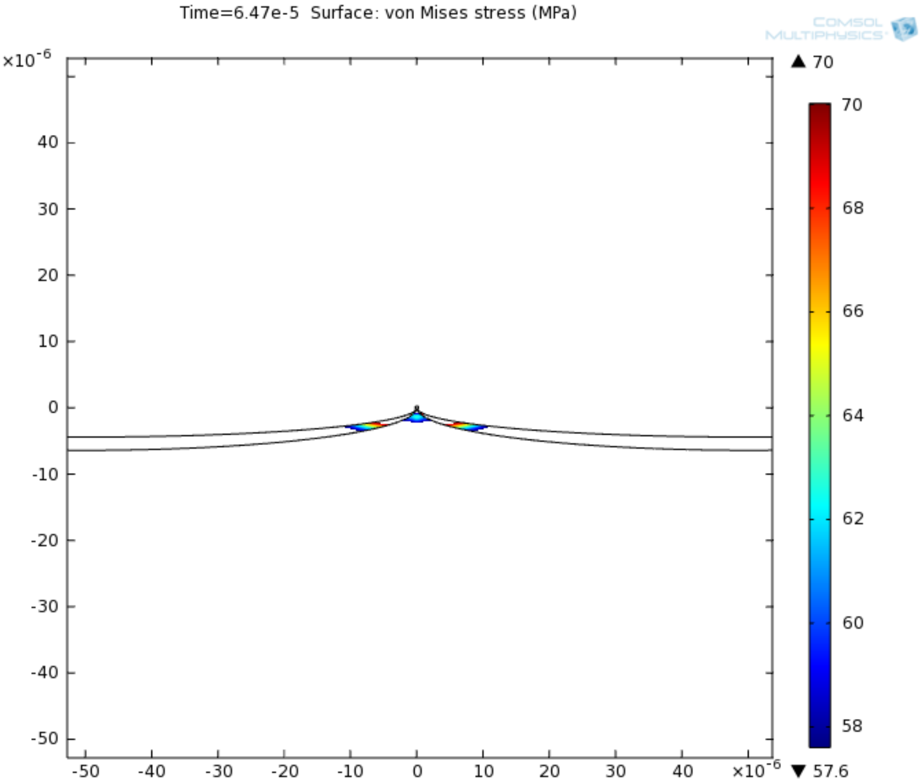


Fig. 9.18 Disposition of the passivated layer and the layer of sampled material, US pressure = 20 MPa

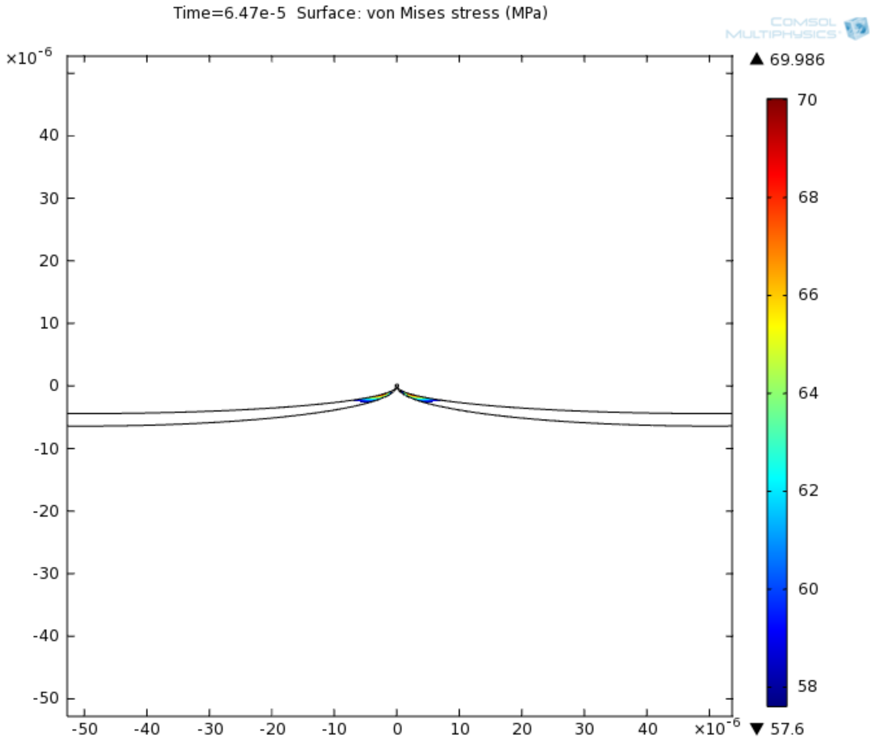


Fig. 9.19 Disposition of the passivated layer and the layer of sampled material, US pressure = 17 MPa

The detailed 2D representation of the material removed by ultrasonic cavitation action combined with electrochemical processing is shown in figure 9.20.

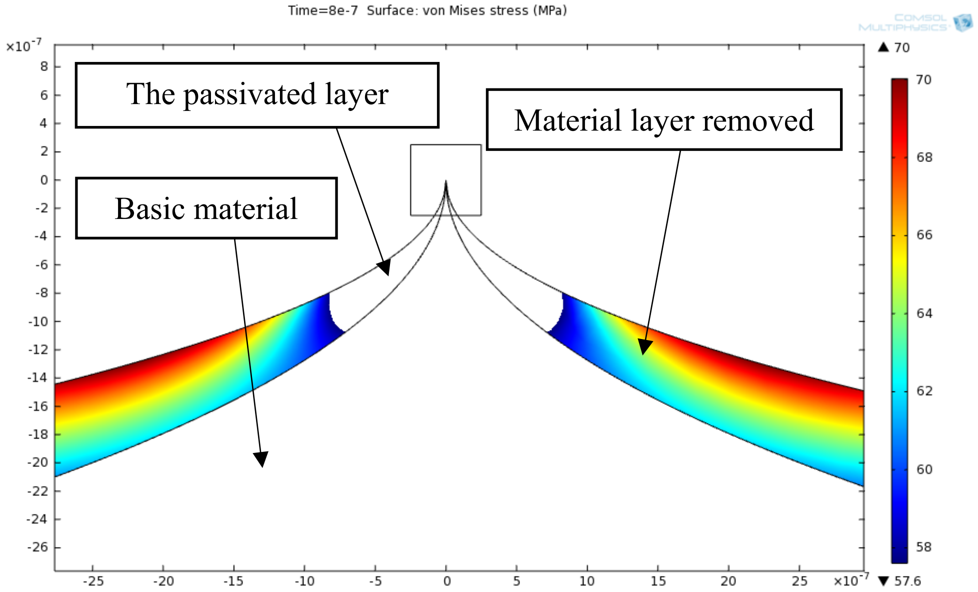
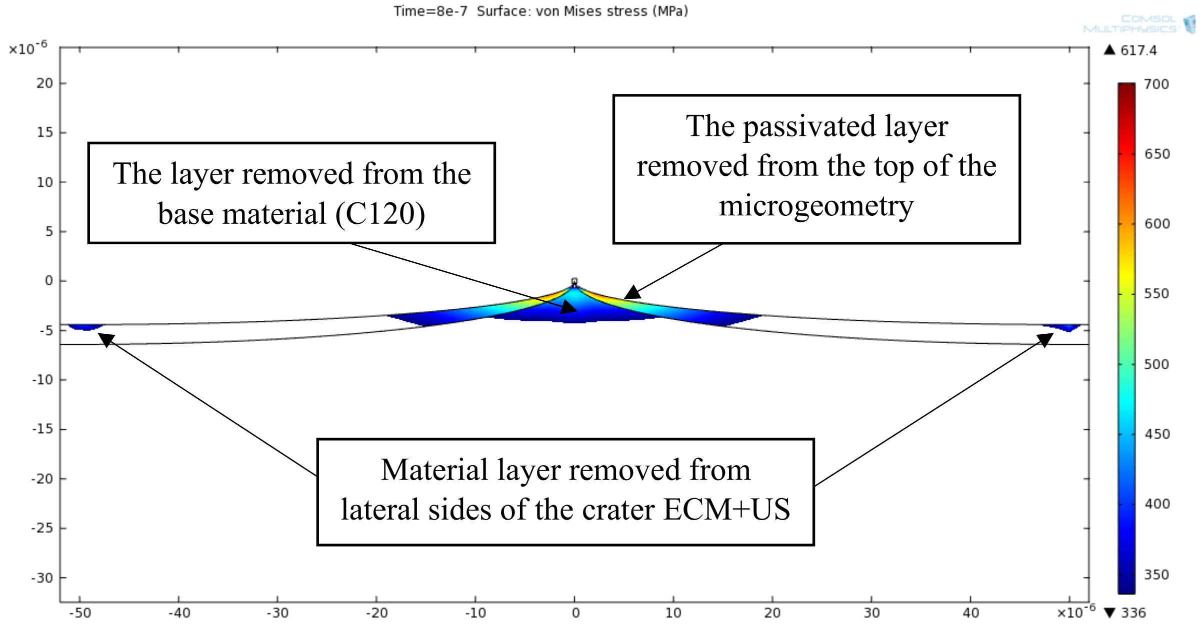


Fig. 9.20 Apportionment of unit effort to depassivation with applied US pressure

9.2.2 Numerical simulation of surface roughness reduction by ultrasonic cavitation

In figure 9.24 are presented the areas of material removed from both the microgeometry peaks and the sides of the crater resulting from ECM+US processing.



The layer removed from the base material (C120)

The passivated layer removed from the top of the microgeometry

Material layer removed from lateral sides of the crater ECM+US

Fig. 9.24 Defining areas of removed material

9.3 Numerical simulation of the material sampling process in the case of steels with Cr and W carbide constituents

In order to study the influence within the material sampling mechanism of the components of Cr and W carbide particles, constituents of the C120 steel from which the test pieces were made, new models were developed using the finite element method, through the software , specialized Comsol Multiphysics (figures 9.32, 9.33).

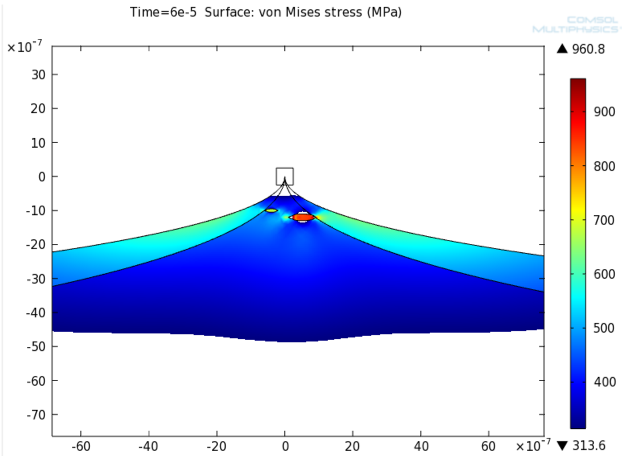


Fig. 9.32 The von Mises unit stresses in the case of the position of the carbide particles relatively close to the area of the micropeaks

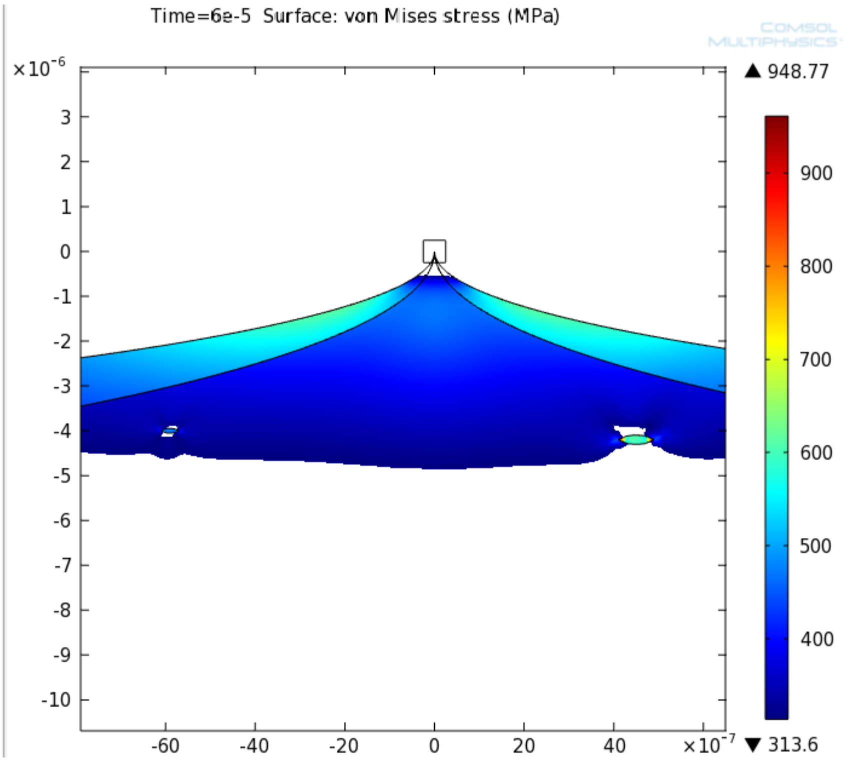


Fig. 9.33 The von Mises unit stresses in the case of the position of the carbide particles at the material sampling limit

9.4 Numerical simulation of electrolyte flow

It was modeled with the finite element method, the flow of electrolytic liquid in the processing gap in the case of tangential flow, adopted in the construction of the technological finishing system, experimental model, because the test pieces and even less the tool-electrode integrated in the ultrasonic chain, are not provided flow holes (figure 9.39).

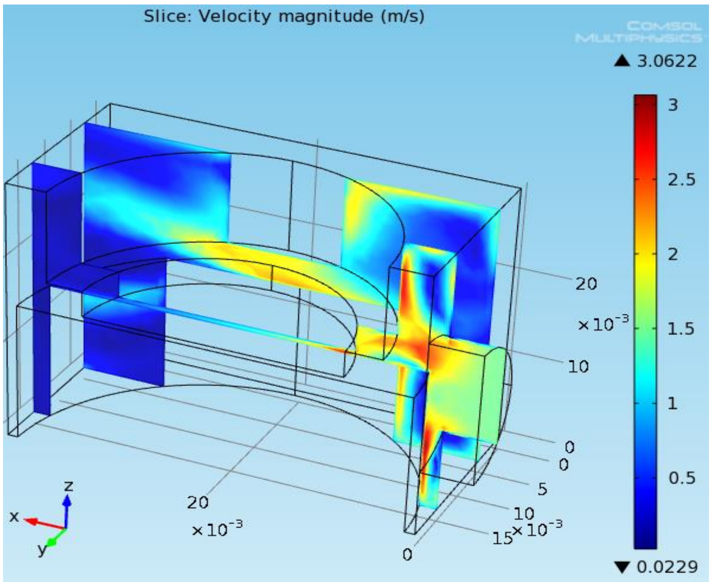


Fig. 9.39 The flow rate of the electrolytic liquid in the working area

The results obtained at the end of the flow pause time are shown in fig. 9.43.

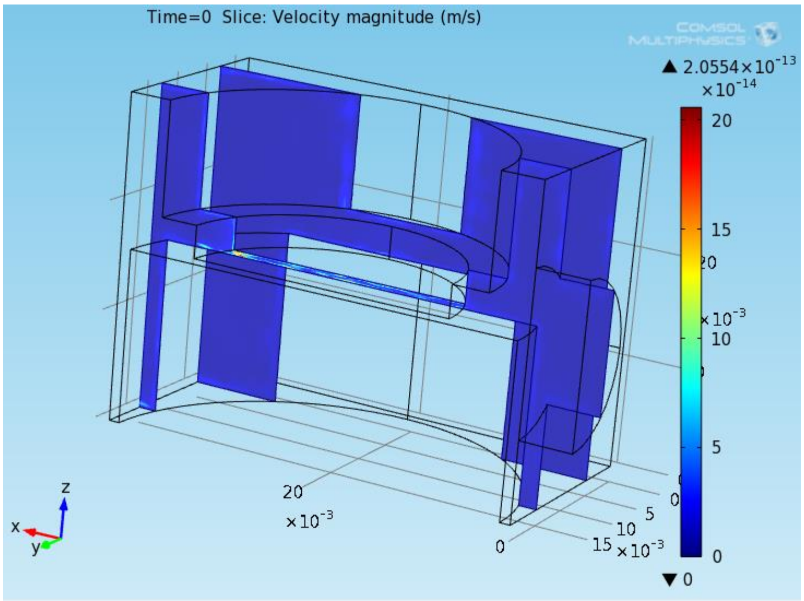


Fig. 9.43 Flow velocity distribution after pause time

9.5 Conclusions

- A multi-model study was carried out in which the value of ultrasonic cavitational pressure was varied to determine the layout and volume of the removed material layer with a C120 steel base structure.

- When modeling the structure of highly alloyed steels with Cr and W, the influence of metal carbide particles in the material removal mechanism was analyzed. It was found that they create conditions for a non-uniform sampling of the material and the production of cavities with dimensions comparable to those of the carbide particles.

- When modeling the tangential flow of the electrolyte solution in the front interstitium of processing, a very low flow velocity results at the exit of the electrolyte, which creates difficulties in the evacuation of the products resulting from the ECM+US process and implicitly, disfavors the smoothing of the surface. Ultrasonically induced cavitational phenomena in the machining interstitium can compensate for this difficult washing of the machining interstitium.

CHAPTER 10.
PRELIMINARY TESTING OF THE ELECTROCHEMICAL - ULTRASONIC HYBRID FINISHING PROCESS ON A LABORATORY EXPERIMENTAL STAND

10.1 Realization of the experimental stand

In order to preliminarily apply the electrochemical processing technology combined with ultrasound, an experimental stand was developed (figure 10.8).

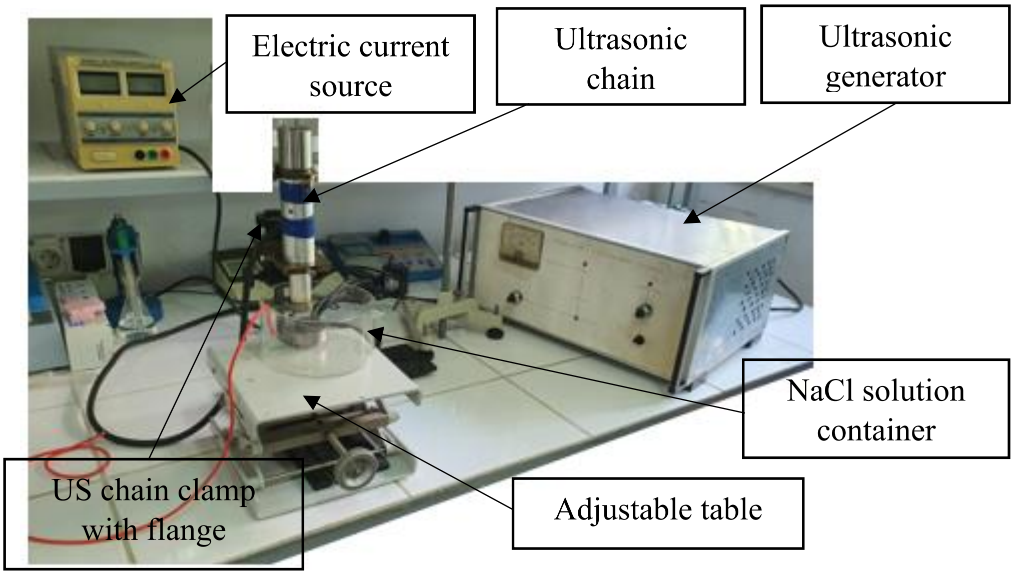


Fig. 10.8 ECM+US experimental stand

10.2 Results of preliminary processing on the experimental stand

The current density on the machined surface was varied. The graphical results for electrochemical machining and electrochemical machining combined with ultrasound are shown in figures 10.17 and 10.18.

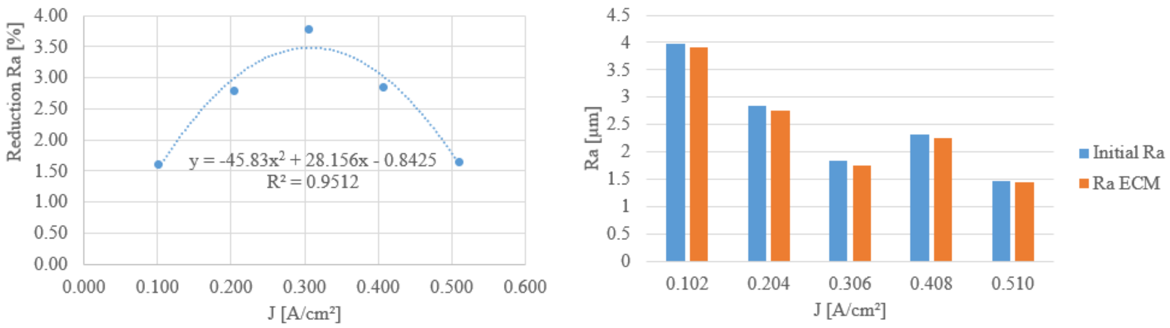


Fig. 10.17 The variation of the roughness of the machined surface in simple electrochemical finishing, the front gap s_F = 0.5 mm, 5% NaCl solution, C120

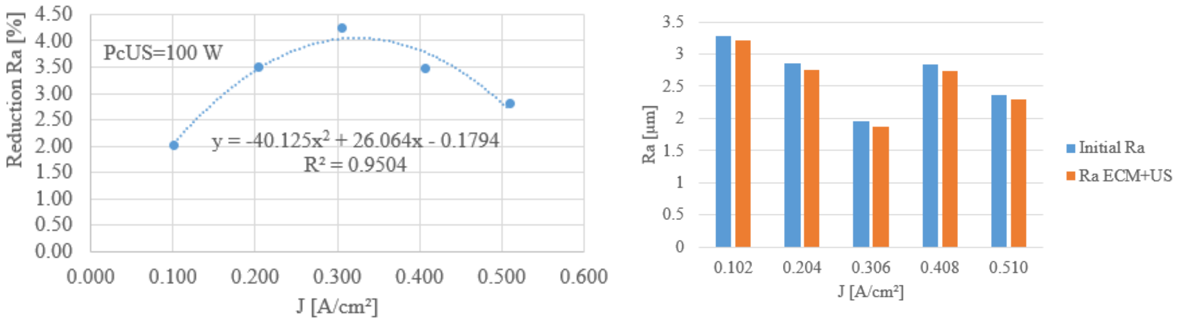


Fig. 10.18 The variation of the roughness of the machined surface in electrochemical finishing combined with ultrasound, front gap s_F = 0.5 mm, 5%NaCl solution, C120

10.3 Conclusions

- Preliminary testing of the electrochemical-ultrasonic hybrid finishing process on an experimental laboratory stand showed that the influence of ultrasound can be beneficial, but it is necessary to design and develop a technological system to ensure the recirculation and filtration of the electrolytic liquid.

- The recirculation and filtration of the electrolytic liquid are important factors that can lead to the improvement of the surface quality of the processed test pieces, and from the point of view of the construction of the equipment, the subassembly that has the role of fixing and orienting the tool in relation to the test part must ensure the parallelism between them, so that a uniform finish is achieved on the entire machined surface and there are no short-circuit moments between the two elements, in the front interstice, where the passivated layer appears on the machined surface, which needs to be removed.

CHAPTER 11.
DETAILED DESIGN OF ELECTROCHEMICAL-ULTRASONIC HYBRID FINISHING EQUIPMENT

11.1 General data

The development of an electrochemical processing equipment combined with ultrasound, namely an ECM cell, involves its 3D design highlighting all the components to be manufactured or purchased commercially from manufacturers. Then, it is necessary to present the functions and structures of the components that make up the equipment.

Catia V5 R21 program was used for 3D design and assembly of all components.

11.2 Development of concepts and components of electrochemical-ultrasonic processing equipment

In figure 11.1 you can see the first concept developed, and in figure 11.3 you can see the second concept.

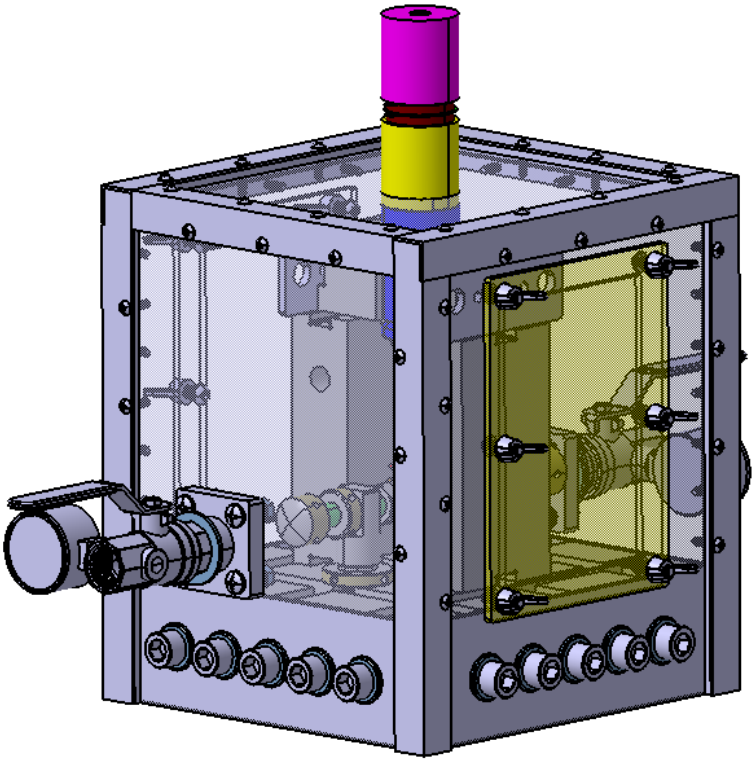


Fig. 11.1 Concept 1 - electrochemical-ultrasonic finishing equipment

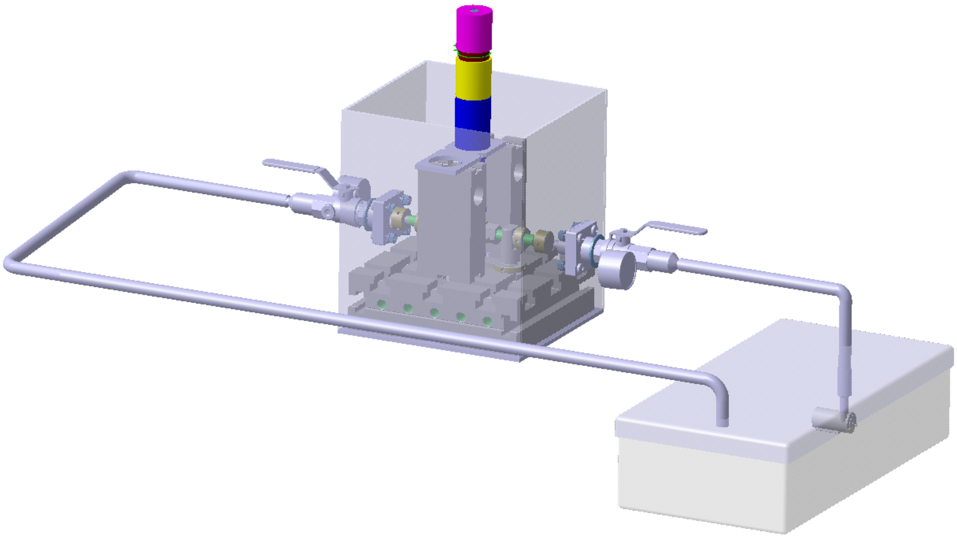


Fig. 11.3 Concept 2 - electrochemical-ultrasonic finishing equipment

11.3 Conclusions

- Two concepts of hybrid electrochemical-ultrasonic processing equipment were developed, the second one also having the electrolytic liquid supply system defined, to analyze which are the most effective solutions in order to manufacture the equipment and finish the surfaces after all commissioning conditions are achived.
- The second concept was chosen for the physical realization, because the tightness is better ensured being a monobloc enclosure construction, the attachment of the US chain is faster and allows it to be oriented in several positions (it can even be fastened with screws to the support bodies on which it sits flange), clamping the US chain with a flange leads to a more accurate resonance condition, since clamping with prisms caused the natural frequency to vary significantly.

Objective Os2 was fulfilled: Development, respectively the design part of an electrochemical-ultrasonic hybrid finishing equipment, with the necessary components: back pressure chamber / electrochemical cell, power source, ultrasound generator, electrolytic liquid tank with filter elements, liquid transfer pump. This objective was also achieved with the help of completing the preliminary testing stage of the hybrid finishing process, ECM+US, as well as with the previous numerical simulations regarding the operation of the ultrasonic chains and some components of the material sampling process.

The secondary objective, Os5: Detailed design of simple and hybrid electrochemical-ultrasonic electrochemical finishing equipment, was also met. On the same equipment, experimental model, simple electrochemical finishing can also be performed comparatively.

CHAPTER 12.
REALIZATION OF HYBRID FINISHING EQUIPMENT, EXPERIMENTAL MODEL

12.1 The actual realization of the equipment

After carrying out the study based on the 3D model, the ECM cell was manufactured which will be used for processing by simple electrochemistry, ultrasonic processing or electrochemical-ultrasonic finishing.

12.2 Assembling the electrochemical-ultrasonic processing equipment

The assembly of the electrochemical-ultrasonic processing equipment involved a series of stages presented in detail in the thesis.

After completing these steps necessary to put the entire technological system into operation, an experimental model, a first verification test can be carried out, then the process of simple electrochemical processing, ultrasonic processing or electrochemical-ultrasonic finishing of the parts can be safely started. sample.

12.3 Conclusions

- The development of an electrochemical-ultrasonic processing equipment involves the creation of a working circuit consisting of the electrolytic cell, the electrolytic tank, a current source, an ultrasound generator coupled by connecting elements provided and tested before the actual start of the processing.

- An electrochemical-ultrasonic processing equipment, in which the part and the tool are immersed in electrolytic liquid, requires ensuring the tightness and flow of the liquid in the area of the front interstice between the part and the tool.

The secondary objective Os6 was achieved: Realization of the ECM+US hybrid finishing equipment. An experimental model was made in modular construction, which was later tested in laboratory conditions.

Through this stage of physical realization of the equipment, the secondary objective was also fulfilled, Os2: Development of an electrochemical-ultrasonic hybrid finishing equipment, with the components: electrochemical cell, power source, ultrasound generator, electrolytic liquid tank with filter elements, pump of liquid transfer.

CHAPTER 13.
TESTING OF ELECTROCHEMICAL-ULTRASONIC HYBRID FINISHING EQUIPMENT UNDER LABORATORY CONDITIONS

13.1 Test methodology

The test methodology was established after several trials, so that all steps are clear, easy to understand and at the same time efficient, so that all parameters characterizing the operation of the ECM+US experimental model, under laboratory conditions, are evaluated.

13.2 Measuring the natural frequencies of ultrasonic chains, adjusting and monitoring the ultrasonic generator

The following steps involve the application of ultrasound, so the generator and the ultrasonic chain were checked to ensure that they operate under resonant conditions (figures 13.4, 13.7, 13.8, 13.9).

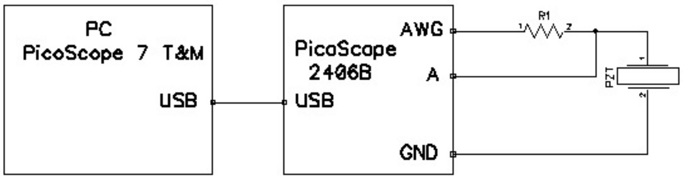
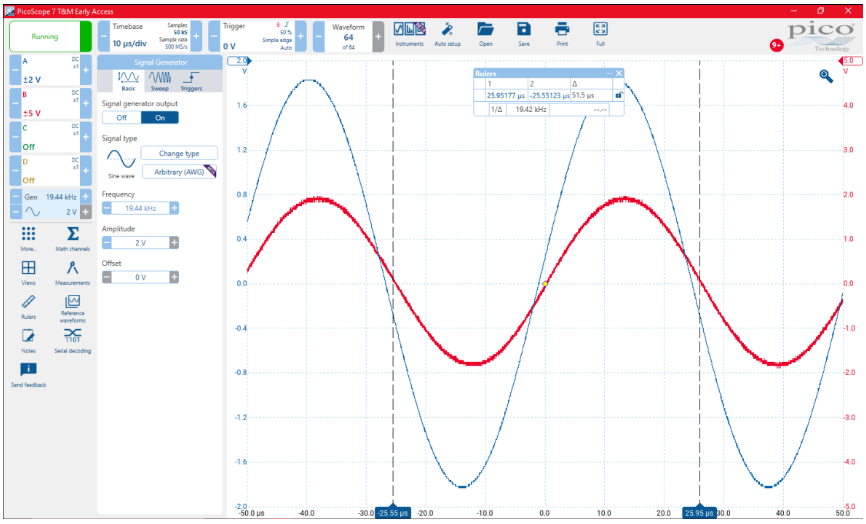


Fig. 13.4 Resonance control of ultrasonic chain - Block Diagram


PicoScope 7 T&M Early Access

Running

Timebase: 10 µs/div; Samples 50 kS; Sample rate 500 MS/s

Trigger: 0 V; B; 50 %; Simple edge; Auto

Waveform 64 of 64

A: DC x1, ±2 V

B: DC x1, ±5 V

C: DC x1, Off

D: DC x1, Off

Gen 19.44 kHz, 2 V

Signal Generator

Signal generator output: Off / On

Signal type: Sine wave

Frequency: 19.44 kHz

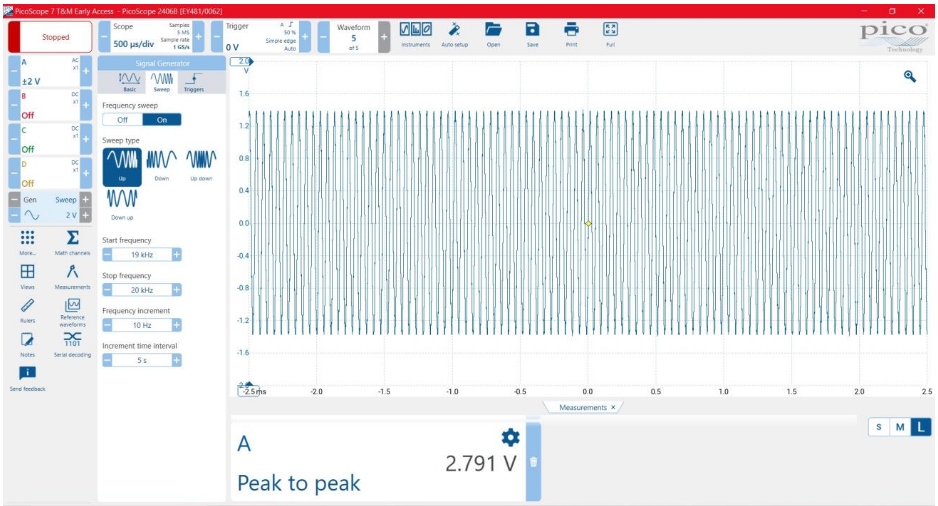
Amplitude: 2 V

Offset: 0 V

Rulers

	1	2	Δ
	25.95177 µs	-25.55123 µs	51.5 µs
1/Δ	19.42 kHz	--.--	

Fig. 13.7 Determination of the own frequency of the experimental acoustic measurement stand



Frequency sweep: On

Sweep type: Up

Start frequency: 19 kHz

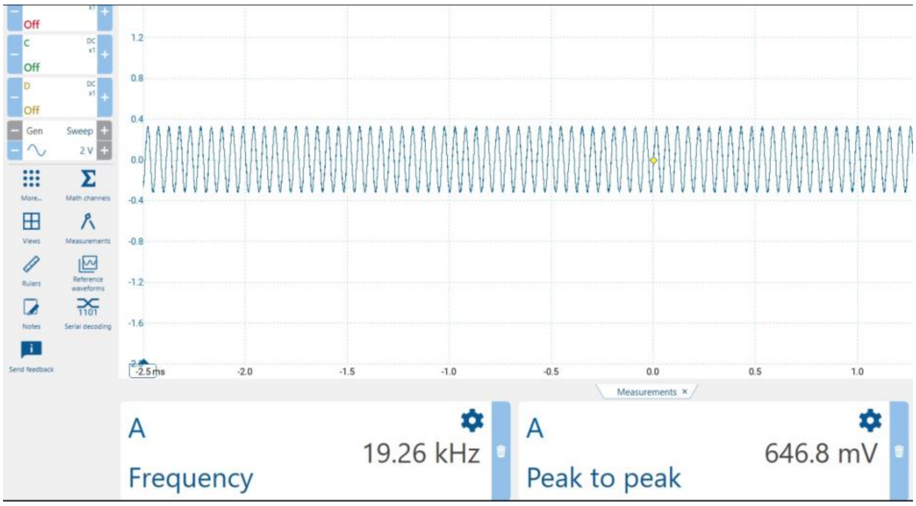
Stop frequency: 20 kHz

Frequency increment: 10 Hz

Increment time interval: 5 s

A
Peak to peak 2.791 V

Fig. 13.8 Own frequency sweep US generator

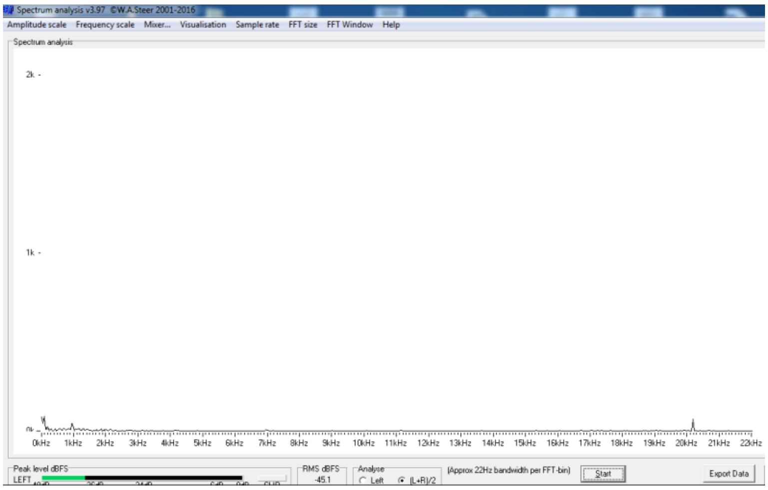


A
Frequency 19.26 kHz

A
Peak to peak 646.8 mV

Fig. 13.9 Own frequency after applying the paint layer

Figure 13.10 shows the background noise diagram.



RMS dBFS -45.1

(Approx 22Hz bandwidth per FFT-bin)

Fig. 13.10 Background noise analysis

Figure 13.11 shows a diagram obtained with the Spectrum Analyzer program.

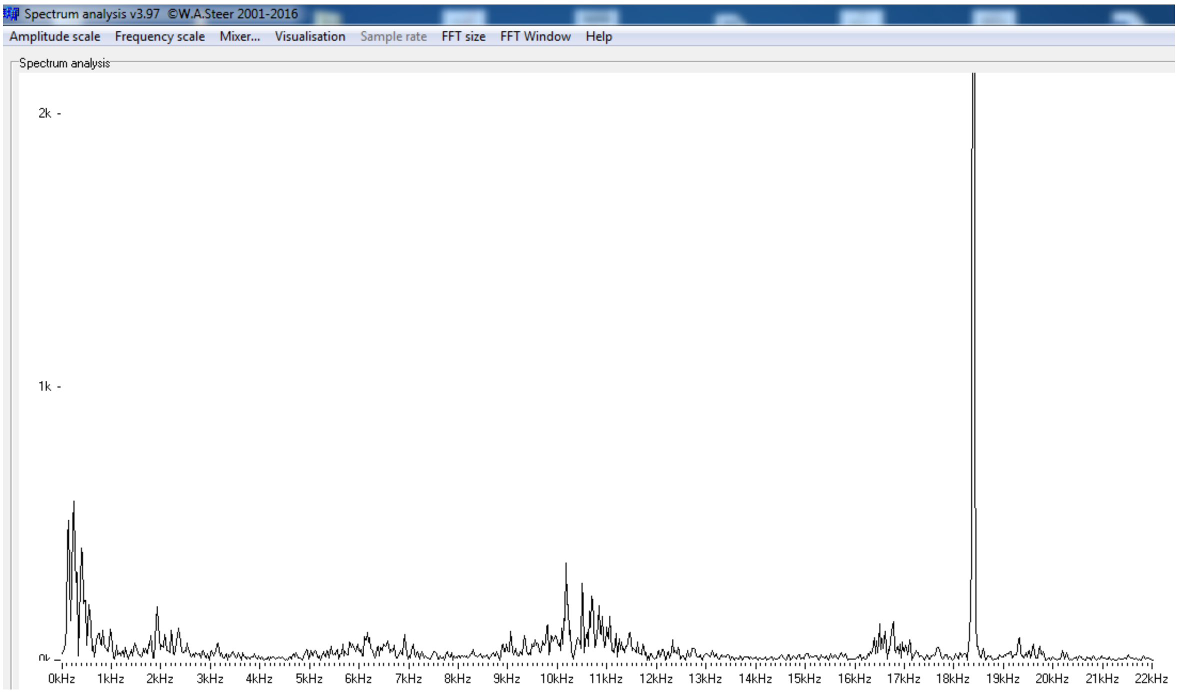


Fig. 13.11 Frequency and amplitude analysis, P=94.8 W

13.3 Realization of the tests in laboratory

After preliminary testing of the operation of the experimental model, the processing process was further applied, under laboratory conditions:

- electrochemical processing (for comparison);
- ultrasonic processing (for comparison);
- simultaneous and successive electrochemical-ultrasonic processing.

These technological variants are to be described in this chapter, the objective being the finishing of the surfaces of the test pieces from different materials with the help of distinct processing regimes, highlighting the advantages and disadvantages in each case.

13.3.1 Electrochemical processing

Figure 13.20 shows the influence of current density J on Ra, during electrochemical processing.

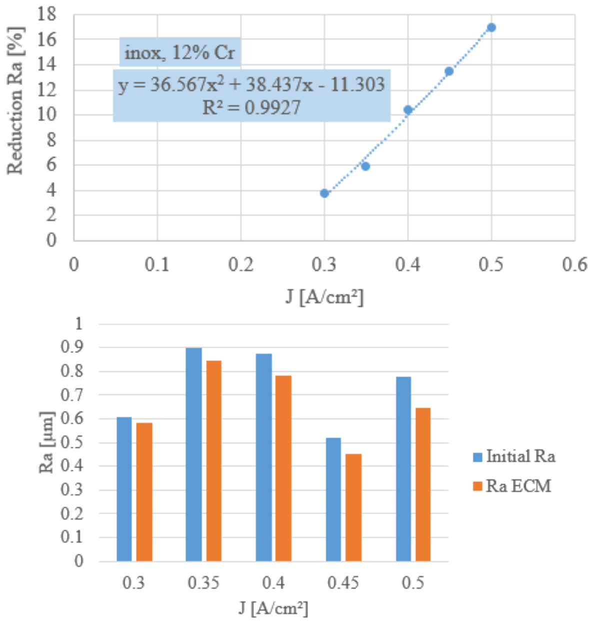


Fig. 13.20 Influence of current density, J on Ra, s_F = 0.5 mm, 5%NaCl solution, 12% Cr stainless steel

13.3.2 Ultrasonic processing

Ultrasonic processing was approached separately to study the contribution of the ultrasonic component within the material sampling mechanism (figure 13.25).

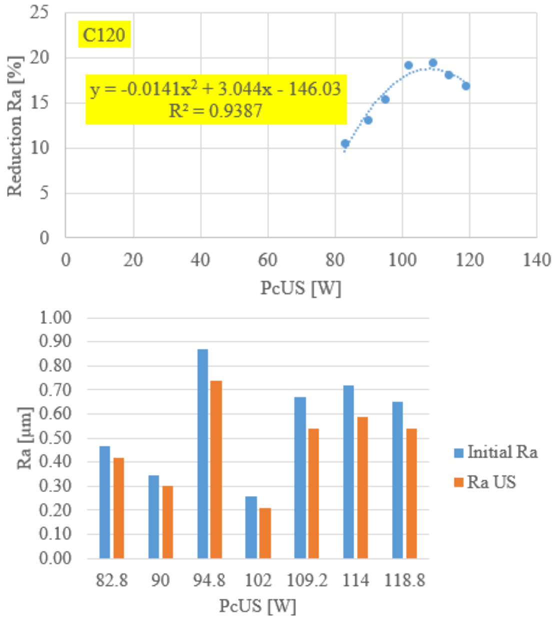


Fig. 13.25 Influence of ultrasonic power consumption, PcUS on Ra, s_F = 0.5 mm, 5%NaCl solution, C120

13.3.3 Simultaneous and successive electrochemical-ultrasonic processing

- **Simultaneous electrochemical-ultrasonic hybrid finishing - method 1**

This processing method proposes the application of *simultaneous* electrochemical-ultrasonic hybrid technology (figure 13.27), following the next steps:

- supplying the ECM cell with 5% NaCl electrolyte.
- break time 30 seconds.
- electrochemical-ultrasonic processing 2 minutes.
- washing time 30 seconds.
- break time 30 seconds.
- repeating the cycle 3 times.

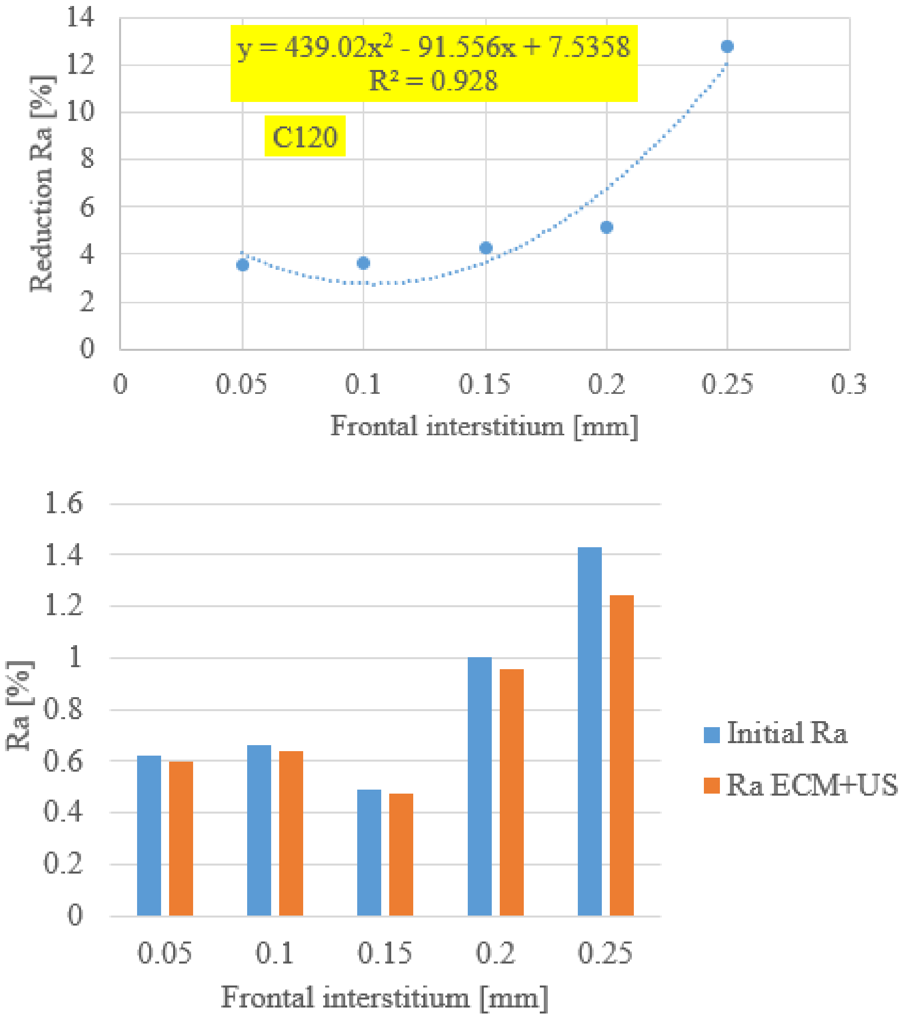


Fig. 13.27 Influence of the frontal interstitium on Ra, 5%NaCl solution, C120

- **Electrochemical-ultrasonic successive hybrid finishing - method 2**

In figure 13.28, the influence of the current density J on Ra can be observed, during the successive electrochemical-ultrasonic processing.

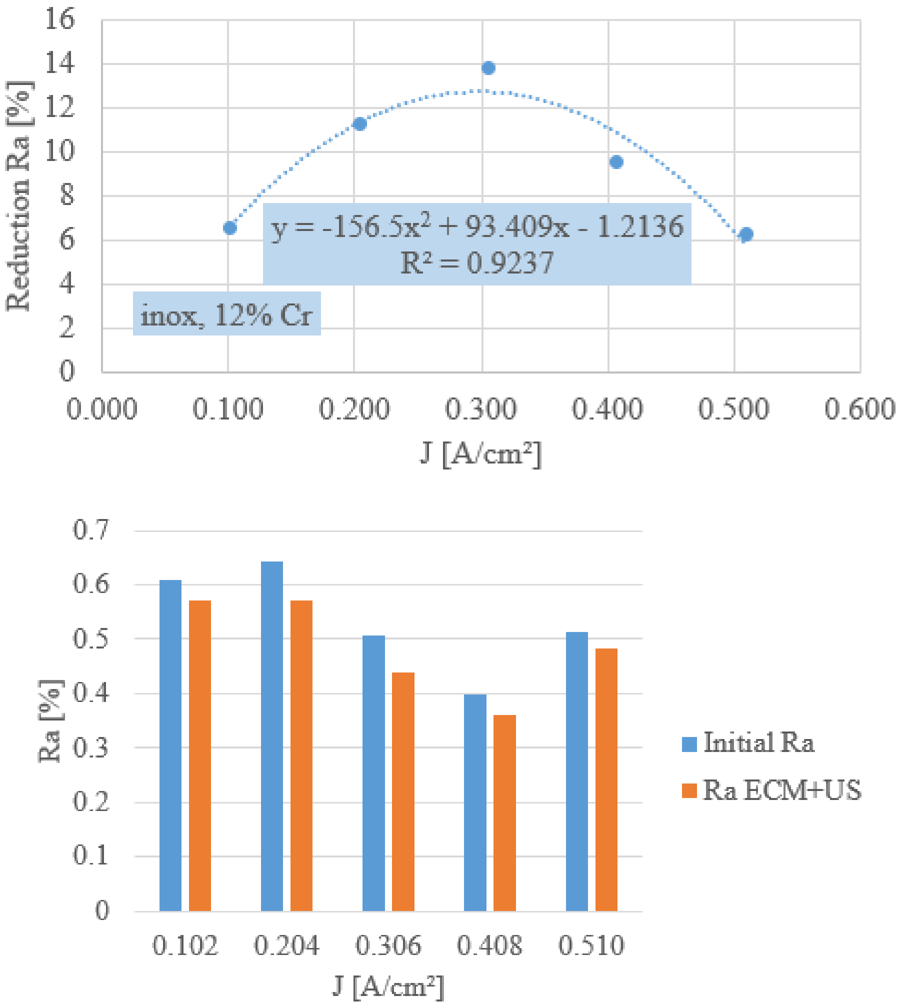


Fig. 13.28 Influence of current density, J on Ra, s_F = 0.3 mm, 5%NaCl solution, 12% Cr stainless steel

- **Electrochemical-ultrasonic successive hybrid finishing - method 3**

A new working method of sequential electrochemical-ultrasonic processing has been established (figure 13.29) which is carried out as follows:

- supplying the ECM cell with 5% NaCl electrolyte.
- break time 30 seconds.
- ultrasonic treatment for 1 minute and 30 seconds.
- start washing with electrolytic liquid 30 seconds.
- break time 30 seconds.

- electrochemical processing for 1 minute and 30.
- repeating the cycle three times.

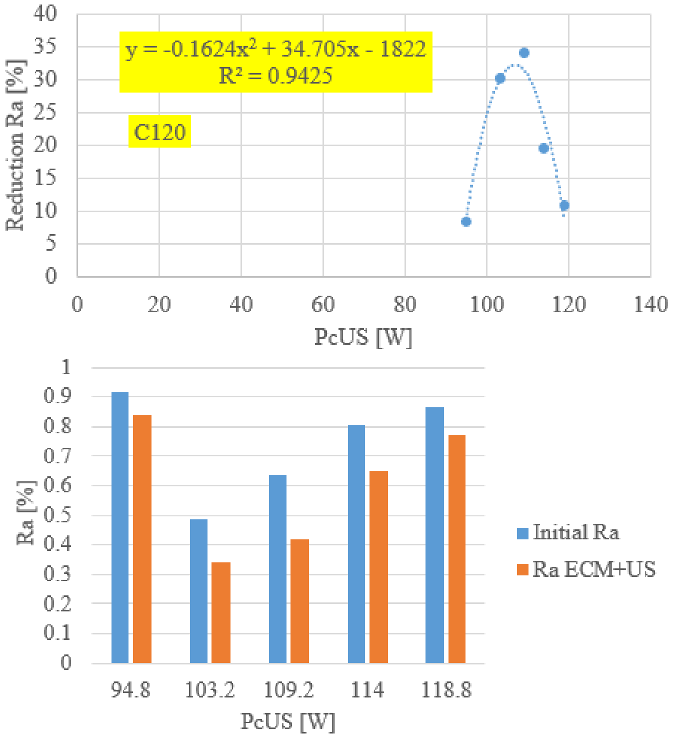


Fig. 13.29 Influence of ultrasonic power consumption, PcUS on Ra, s_F = 0.7 mm, 5%NaCl solution, C120

13.4 Scanning electron microscope analysis of machined surfaces

An electronic scanning microscope, SEM QUANTA INSPECT F50 (figure 13.32), was used to highlight the morphological structure of the processed surfaces according to the parameters of the processing regime used.

Fig. 13.32 SEM QUANTA INSPECT F50

Figures 13.35, 13.36, 13.54, 13.55 show some of the SEM results.

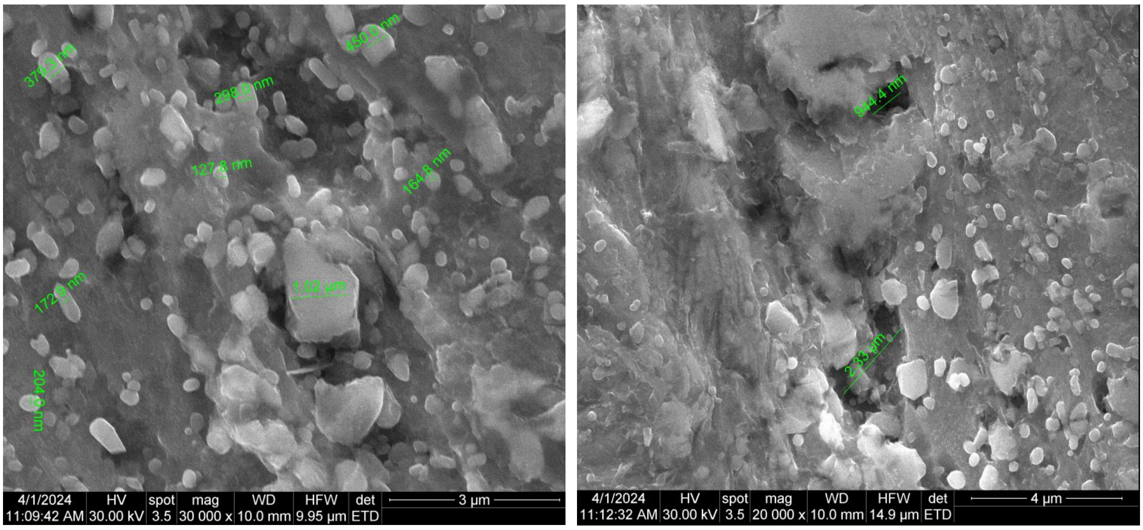


Fig. 13.35 SEM ECM images

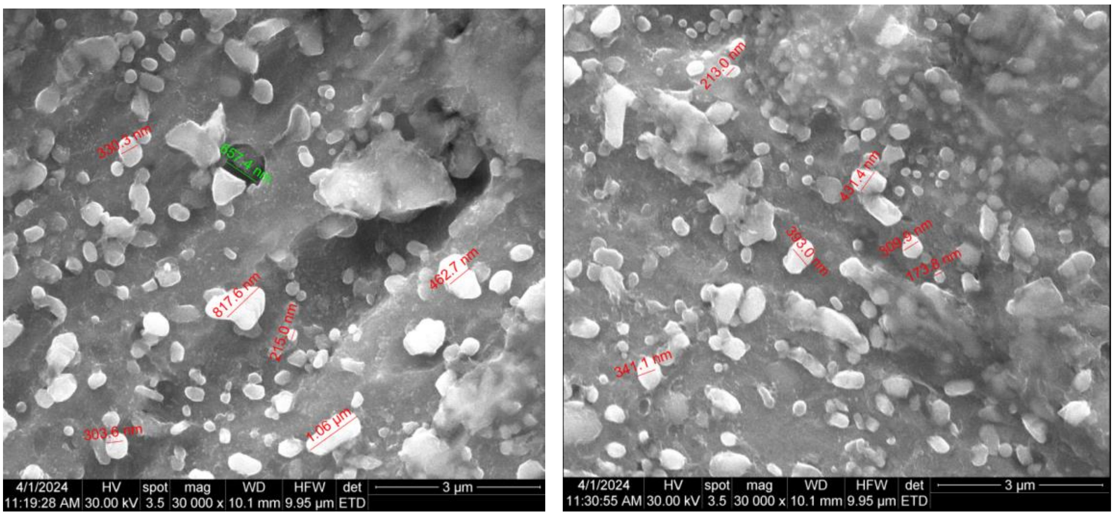
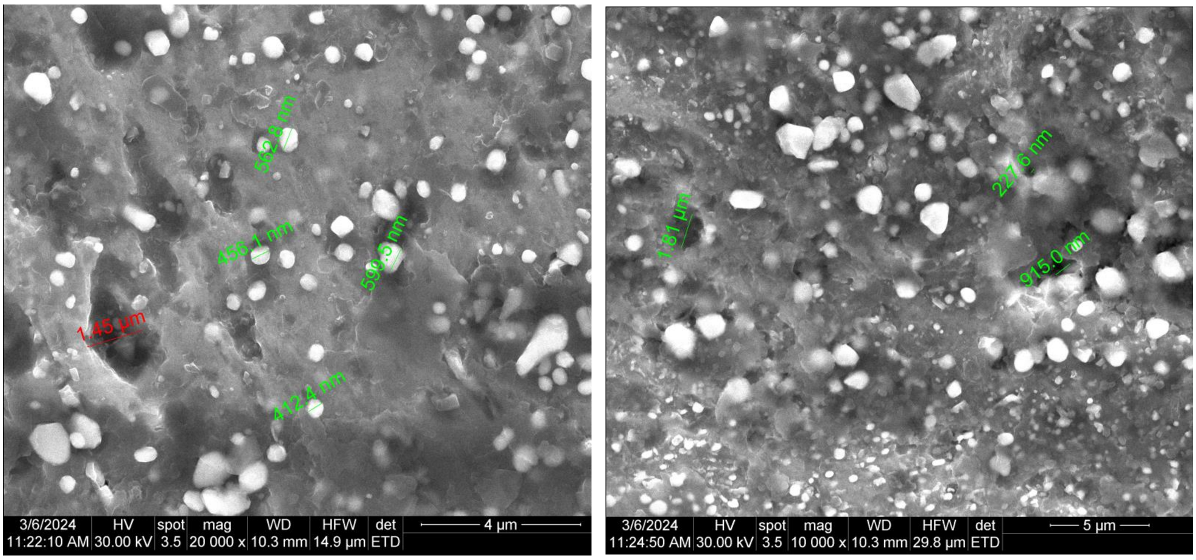


Fig. 13.36 SEM ECM images



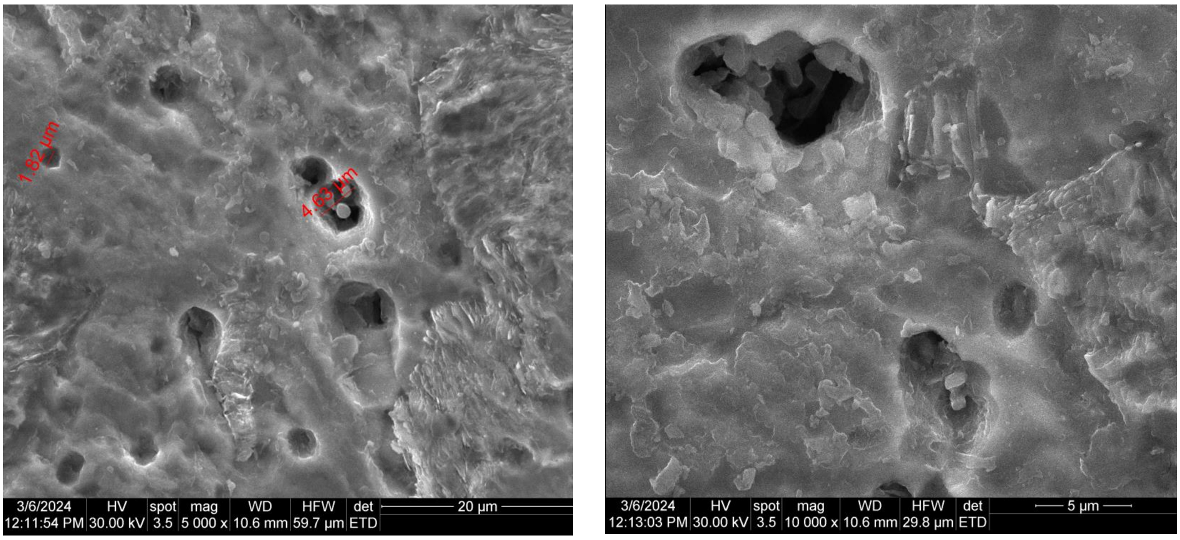
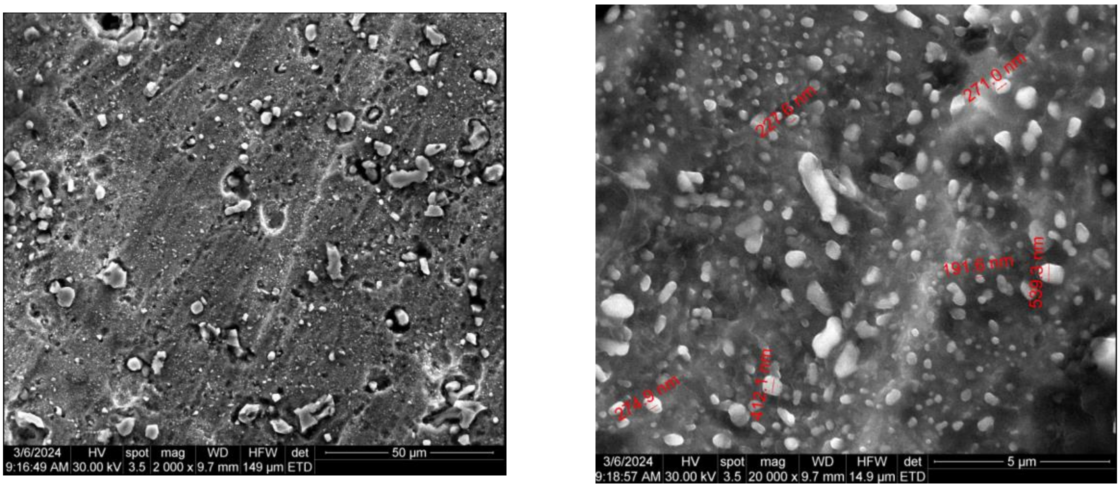


Fig. 13.54 SEM ECM+US images



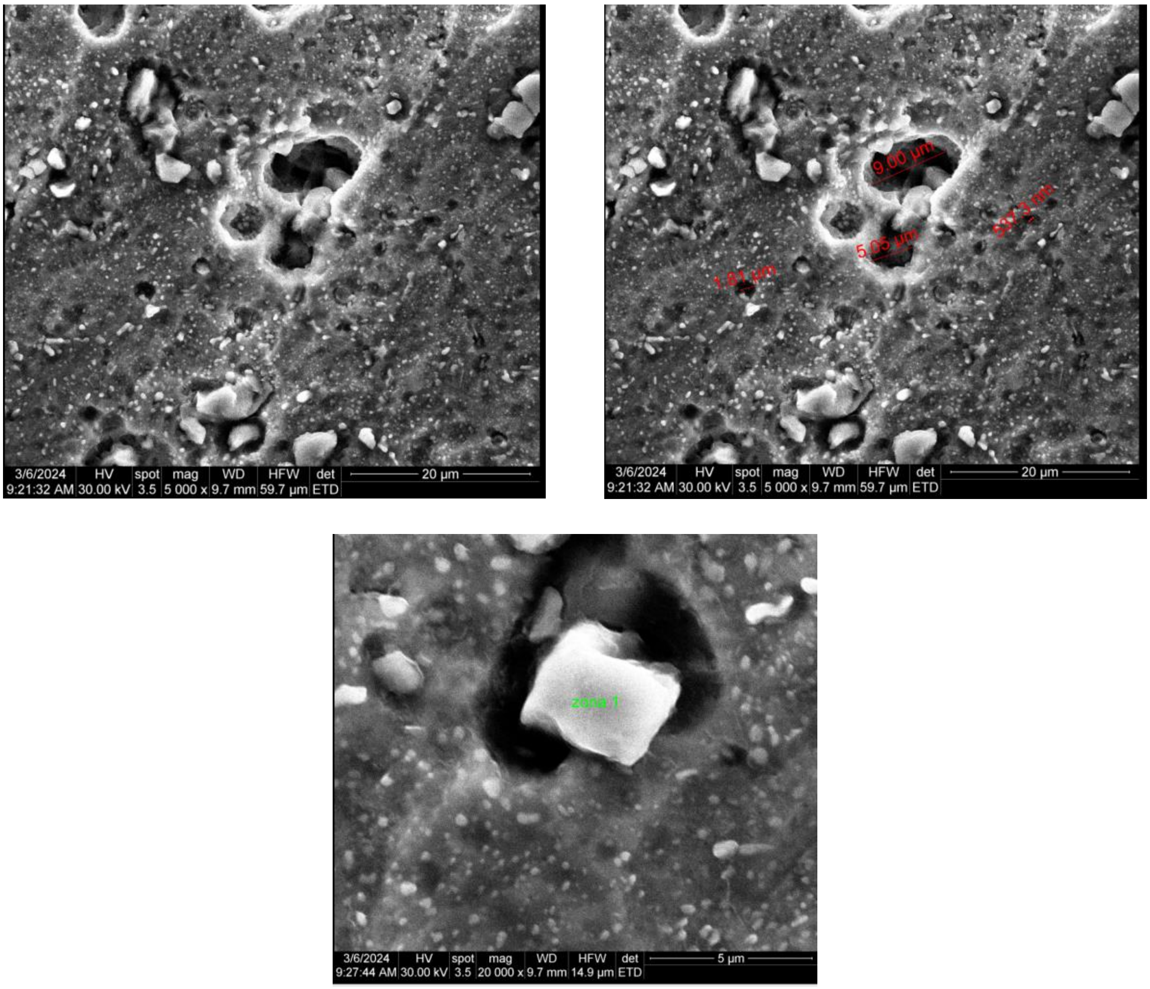


Fig. 13.55 SEM ECM+US images

13.5 2D analysis and 3D scanning of machined surfaces

After the presentation of the data obtained according to each method and processing regime, the analysis carried out under the scanning electron microscope and the interpretation of the images, before formulating the final conclusions of the research, 2D and 3D roughness measurements were made using the MarSurf GD140 device (block diagram in figure 13.66).

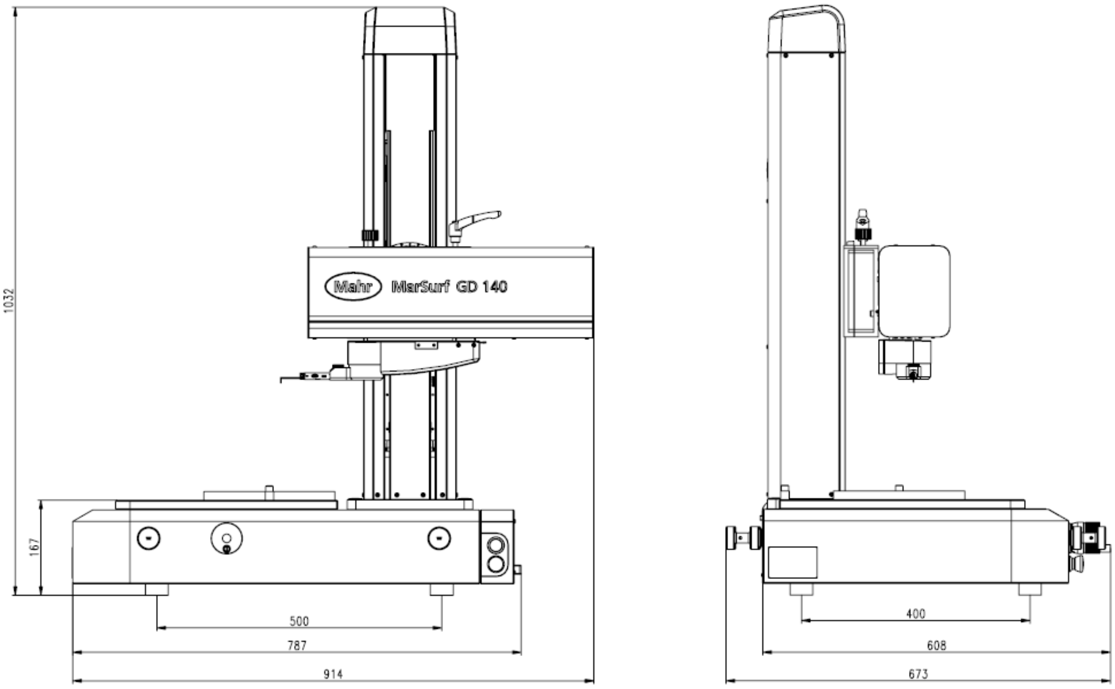


Fig. 13.66 MarSurf GD140 block diagram and dimensions [150]

13.6 Establishing the causes of non-conformities and solutions to increase the technological performance of the hybrid, electrochemical-ultrasonic finishing equipment

- **Performance analysis of the electrochemical component**

Technological solutions for increasing the performance of the finishing process in connection with the current density consist in determining optimal values, under laboratory test conditions, for high-alloyed steels containing Cr and W carbides with the objective function of reducing the percentage of the initial roughness of the processed surface. The optimal current density values are in the range of 0.3-0.4 A/cm^2 *and have led to percentage reductions in Ra of a maximum of 23%.*

The technological solution that would lead to the removal of the non-conformity regarding the increase in the roughness of the processing surface, related to the processing time, is that it does not exceed the critical value of 2-3 min, after which the obtained roughness begins to increase as a result of an additional sampling of material, from the area of microdepressions of the processed surface.

In order to remove the causes underlying the production of these non-conformities, the following technological solutions can be used:

- *increasing the value of the front processing gap,* s_F*, in order to reduce the hydraulic resistance in the processing gap;*
- *increasing the flow and implicitly the flow rate and pressure characteristics provided by a pump with superior characteristics, suitable for the corrosive action of the electrolyte solution.*

In order to remove the causes that led to these types of non-conformities, the following solution was adopted, to ensure uniform flow and kinetic stabilization of the electrolytic liquid when applying the electrochemical component: ***successive ECM and US processing, with the introduction of a sufficient pause time****, during which the flow was stopped - the electrolyte inlet velocity being zero.*

This solution, which ensured superior results of the **successive** hybrid finishing process, ECM+US compared to the **simultaneous** variant, validates the finite element modeling of the flow in the processing gap presented previously, approached in two stages: stationary turbulent flow and flow dependent laminar time with the cancellation of the entry speed of the electrolyte in the electrochemical cell.

13.7 Conclusions

- Electrochemical or electrochemical-ultrasonic processing involves monitoring and keeping under control the following parameters: current intensity, processing time, working gap, temperature, electrical resistivity, respectively the concentration of the electrolyte, the frequency transmitted by the ultrasound generator, ensuring the resonance frequency between the transducer and concentrator.
- It was found that successive electrochemical-ultrasonic processing is superior from the point of view of the quality of the processed surface compared to simultaneous electrochemical processing; turbulent flow in tangential conditions does not favor the surface smoothing process; therefore, the successive variant was adopted, in which there is a pause time after the ultrasonic processing, in which the cancellation of the flow rate is achieved (the electrolytic liquid is stationary) and then electrochemical processing is carried out - the peaks of the microgeometry are dissolved anodically.

By achieving the secondary objectives stated in chapter 5, it can be stated that the main objective of the thesis, Op: Designing, simulating the operation, making and experimenting of a hybrid electrochemical-ultrasonic finishing equipment (ECM+US), has also been achieved.

CHAPTER 14.
FINAL CONCLUSIONS, ORIGINAL CONTRIBUTIONS AND FUTURE RESEARCH DIRECTIONS

14.1 Final conclusions

According to the critical analysis of the addressed field presented in the current stage of the first part of the thesis and the carrying out of the research activities in the second part regarding the realization, testing of the hybrid, electrochemical-ultrasonic finishing equipment, experimental model, the following final conclusions were formulated:

1. The hybrid electrochemical-ultrasonic finishing equipment, experimental model, was made and tested. For this, the stages necessary to move from the concept phase, conceptual design, level 2 of technological maturity – technology readiness level 2, TRL2, to the testing phase in laboratory conditions, TRL 4, were completed.

2. The jump from the TRL 2 level to the TRL 4 level required the completion of some intermediate stages, which consisted of:

2.1) modeling and numerical simulation of ultrasonic concentrators to achieve the resonance condition, which contributes to reducing the manufacturing preparation time and improving the disadvantage regarding the lack of flexibility of the ECM+US hybrid technology;

2.2) modeling and numerical simulation of concentrators covered with plastic, electrically insulating materials to prevent accidental electrochemical processing, under the conditions of ECM processing with the concentrators immersed in the electrolytic liquid;

2.3) modeling and numerical simulation of the process of depassivation and sampling of the peaks of the microgeometry of the processed surface, the contribution of the ultrasonic component within the material sampling mechanism of the hybrid electrochemical-ultrasonic finishing process;

2.4) modeling and numerical simulation of the flow of the electrolytic liquid in the front interstitium of processing, which allowed the use of the turbulent, tangential flow regime as well as the adoption of a processing method with the introduction of a break to stop the flow in order to create conditions of kinetic uniformization of the electrolytic liquid before applying the electrochemical component of the hybrid finishing process;

2.5) modeling and numerical simulation of the sampling of Cr and W metal carbides, constituents of high-alloy steels, from which processed test pieces were made in order to test the hybrid, electrochemical-ultrasonic finishing equipment;

2.6) the detailed design of the finishing equipment, starting from the conceptual design of the hybrid electrochemical-ultrasonic finishing equipment, which included the electrochemical processing cell, the ultrasonic chain, which integrated the tool-electrode, the ultrasonic-chain clamping devices and sample parts, electrolyte solution recirculation circuit, electrolytic liquid pool, recirculation pump and filter elements;

2.7) the execution of the electrochemical-ultrasonic hybrid finishing equipment, the creation of non-standard components and the purchase of some components, their adjustment and assembly;

2.8) testing the electrochemical-ultrasonic hybrid finishing equipment in laboratory conditions, which included several stages; testing the generator coupled with the ultrasonic chain to achieve the resonance condition, testing the simple electrochemical component, testing the ultrasonic component separately; hybrid, electrochemical-ultrasonic finishing processes in simultaneous and successive mode;

3. When testing the equipment, processing methods were established using the hybrid electrochemical-ultrasonic finishing process. Under the existing laboratory experimental conditions, the best results were obtained with successive methods, which involved a cycle consisting of ultrasonic depassivation, electrolytic liquid flow on the machined surface, flow pause time, application of electrochemical smoothing, ultrasonic processing, depassivation and surface smoothing by ultrasonically induced cavitation in the machining gap and restarting the cycle;

4. Optimum values of some key parameters of the ECM+US processing regime were established, namely the current density J on the processed surface, as well as the power consumed on the ultrasonic chain, with the objective function being the percentage reduction of the roughness of the processed surface in relation to initial roughness;

5. The causes that can lead to non-conformities related to the experimental model of hybrid, electrochemical and ultrasonic finishing have been identified, as well as improvement solutions in order to increase technological performance.

14.2 Original contributions

Analyzing the results of the research carried out in the framework of the doctoral thesis *"Research on hybrid electrochemical-ultrasonic finishing processing"*, a series of original contributions, both theoretical and applied, were established.

- **Theoretical contributions**

1. Classification of non-conventional hybrid technologies in the following categories, as follows:
   - after the contribution made by the secondary / secondary component or components: combined hybrid technologies, where the secondary component contributes directly to the sampling of the material; assisted hybrid technologies, where the secondary component or components only create the conditions for increasing technological performance;
   - by means or element of assistance of hybrid technologies: with vibrations, laser, fluids and magnetic field;
   - placing the ECM+US technology in the category of hybrid combined processing due to the fact that ultrasound directly contributes to the removal of the material not only by removing the passivated layer from the processed surface (depassivation), but also the peaks of the microgeometry, reducing the roughness;
   - the combined electroerosive-ultrasonic hybrid processing was included in the same category because it was demonstrated that ultrasound through the controlled effect of cavitation induced in the processing gap contributes directly to the removal of the material, mainly by reducing the roughness of the processed surface;
   - by the number of combined components; two or more components;
   - according to the mode of assistance; *simultaneously* - the simultaneous action of the components on the processed material or *successively* - the consecutive action of the components on the processed material.

2. The transition from the concept phase of an electrochemical finishing equipment combined with ultrasound - maturity level (Technology Readiness Level) TRL 2, to that of an experimental model of the electrochemical finishing equipment combined with ultrasound - tested under conditions of laboratory, respectively TRL 4.
3. Formulation of the general function, main and secondary functions of the electrochemical-ultrasonic finishing equipment and the design of its architecture.

- **Application contributions**

- Numerical simulation of the effect of the ultrasonic component in the process of electrochemical finishing, depassivation and reduction of the roughness of the processed surface and validation of the computerized model in laboratory conditions;
- Numerical simulation of the material sampling process in the case of high-alloyed steels, containing Cr and W carbides and the explanation of the formation of microcavities on the processed surface when the ultrasonic power is increased, as well as the validation of the computerized model in laboratory conditions;
- Numerical simulation of the electrolyte flow in the front processing gap, approached in two stages, which also led to the establishment of the successive hybrid, electrochemical-ultrasonic finishing method;
- The two stages of numerical simulation consisted of: stationary turbulent flow related to the washing of the processing interstitium; laminar flow dependent on time, related to the pause time for creating the conditions for kinetic uniformity of the electrolyte solution on the processed surface when applying the electrochemical component;
- Modeling and numerical simulation of ultrasonic chains in order to obtain the resonance condition and substantially reduce the manufacturing preparation cycle, as well as improve the disadvantage of ECM+US technology regarding reduced flexibility;
- Numerical modeling and simulation of the concentrators under the conditions of application on their surface of various polymeric materials in order to avoid corrosion when immersed in the electrolytic liquid;
- Evaluation of the influence exerted upon the application of each insulating material on the concentrators' own frequency;
- The modeling of a stepped cylindrical concentrator with a flared end, which allows the use of tool-electrodes of various sizes, the realization of the ultrasonic chain that includes this type of concentrator and the experimental validation of the computerized model;
- The design from modular elements of the electrochemical finishing equipment combined with ultrasound, experimental model, so as to allow high flexibility, easy adaptation to other shapes and sizes of the workpieces;
- Realization of the electrochemical finishing equipment combined with ultrasound - experimental stand type for preliminary experiments;
- Preliminary experimentation of the electrochemical finishing equipment combined with ultrasound – experimental stand;
- The design of the modular construction of the electrochemical finishing equipment combined with ultrasound – experimental model, which includes the ultrasonic chain, the ultrasonic chain and workpiece clamping devices, the electrochemical cell, the electrolytic liquid supply circuit;

- Realization of the equipment in modular construction of electrochemical finishing combined with ultrasound – experimental model;
- Testing the electrochemical finishing equipment combined with ultrasound - experimental model, identifying the causes of non-conformities and finding solutions to increase the technological performance of the hybrid finishing process, ECM+US;
- Obtaining the maturity level, TRL 4, of the electrochemical-ultrasonic finishing equipment in modular construction which involved testing its operation in laboratory conditions;
- Establishing the causes that led to the production of non-conformities in the operation of the experimental model of electrochemical-ultrasonic hybrid finishing and the formulation of solutions to contribute to removing these causes and increasing the technological performance of ECM+US finishing.

14.3 Future research directions

Analyzing the results obtained in the doctoral thesis, a series of future research directions were established that integrate current technological solutions, presented in detail in the thesis.

All this can contribute to keeping the technological system under control, as well as the implementation of reaction loops that maintain the process in optimal parameters in real time, based on artificial intelligence algorithms, in accordance with the current technological level reached by the development of the Internet of Things (IoT).

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