Aspects concerning ultra-acoustic energy utilization in joining techniques of polymeric materials in automotive industry

O. Oancă[1], N. A. Sîrbu[1,2]

[1] National R&D Institute for Welding and Material Testing - ISIM Timisoara, Romania;
[2]POLITEHNICA University of Timisoara, Romania

E-mail: octavian.oanca@isim.ro

Keywords

Ultrasonic joining, thermoplastic materials, acoustic plasticization, thermo-plastic deformation.

1. Theoretical consideration regarding the particularities of the assembly by ultrasonic joining of the plastic materials

Comparing to the conventional welding processes, ultrasonic joining of the materials represents a domain with a reduced general utilization, but with high development prospects and dissemination in the following fields: automotives, electro-technical industry, electronics, medicals, pharmaceutical industry, cosmetics, packing industry, etc.

The paper represents a putting into account with aspects concerning the advantages of ultrasonic utilization in materials joining, as well as particular aspects concerning the experimental development of the joining technologies within the laboratory “Centre of Excellency in Ultrasonic Welding CEX-US” from ISIM Timisoara, by investigation of phenomena in the process of ultrasonic welding of the thermoplastic materials and the interest for innovative development of technologies for materials joining, in order to storage the new knowledge and with the goal of alignment at the European standard in the field.

The ultrasonic joining of the plastic materials is determinate by the induced effects of the ultrasound action at the contact surface between the two samples by micro vibration with ultrasonic frequency.

The basic diagram used for joining of plastic materials is presented in the Figure 1.

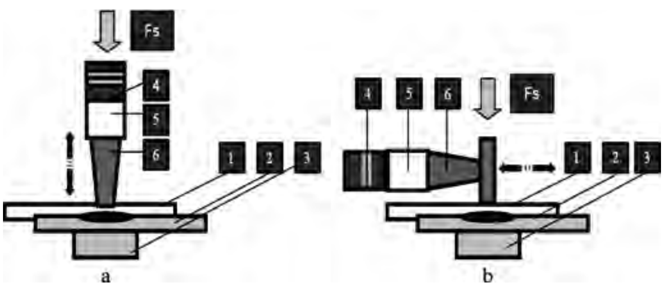


Figure 1. Principle of ultrasonic joining of the plastic materials.

The materials 1 and 2 for joining are placed on the anvil 3. The ultrasonic vibrations are produced by the transducer 4, concentrated and focalized on the joining area using an ultra-acoustic energy concentrator 5 and the sonotrode 6. In order to realize the adequate conditions for joining, the ultra-acoustic assembly is pressed with a force Fs on the material to be joined. Direction of the pressing force can be:

- in the same direction with the ultrasonic oscillations (figure 1a),
- perpendicular on the ultrasonic oscillations (figure 1b).

Energy absorption of the mechanical oscillations is determined by the acoustic impedance of the joining material and also by the existing contact between the welding pieces. The heating is developed like a consequence of the three type of friction which exists during the welding process:

- internal friction with heating effect in all material volume,
- external friction in the contact area between plastic material-plastic material,
- friction between plastic material and sonotrode.

The resulted heating makes that the great part of thermoplastic materials to start melting in a very short time (normally less than a second). The temperature in the joining area must be lower than minimum temperature which, in normal conditions, determines possible damages the material and higher than temperature whereupon a durable welding is obtained.

The steps for ultrasonic welding of the plastic materials consist in the heating of joining materials until the plastic state temperature is reached, succeeded by the realization of the connections in order to allow the obtaining of a durable welding.

The various schemes which stay in present at the basis of the ultrasonic welding of plastic materials allow the classification of this process according to the type of ultrasonic energy assignment.

Taking into account the assignment type of the ultrasonic energy related to surfaces for joining two welding methods are known:

• *Contact welding or ultrasonic welding in near field* presented in Figure 2a. It is the ultrasonic welding process that is obtained when the sonotrode is positioned as near is possible by the weld area (maximum distance is 6mm).

This method is used for joining soft plastic materials like PVC plasticized, being obtained overlap joining.

• In the case of *ultrasonic welding in far field or by transmission*, presented in figure 2b, the ultrasonic oscillations of the sonotrode are applied in a specified point or on a small section of the upper surface of the piece.

Transmission and uniform distribution of the ultrasonic energy, in this case, depend on the capacity of materials to transmit mechanical vibrations. From this reason, welding in far field is recommended for joining hard plastic materials like polystyrene, polymetacrilate, obtaining butt joining or projection welding by overlapping.

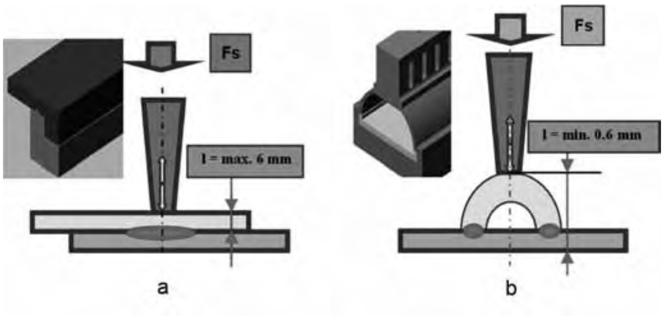


Figure 2. Principles of ultrasonic welding of the plastic materials.

The main criteria regarding *characterization of the welding behavior of the plastic materials* is represented by the amortization factor ß of the oscillations amplitude in the considered plastic materials:

$$ß = \omega \eta /2 (\rho / E)^{1/2} \qquad (1)$$

where:

ω - pulsation of the oscillation;

ρ – material density;

E – elasticity modulus for plastic material;

η – ratio between power modulus and elasticity modulus.

The amortization factor *ß* of the amplitude oscillations characterizes the intensity energy absorption of the mechanical oscillations and determines the percent of mechanical energy transformed in heat in the contact area between joining pieces.

If amortization factor *ß* is larger, then the joining process by welding becomes more difficult.

Welding capability of plastic materials related to the amortization factor *ß* defines in principal three groups of plastic materials:

• Group A: $ß < 0.35 cm^{-1}$, hard plastic materials which can be welded in very good conditions using ultrasounds. Within this group are PMMA (polymetilmetacrilate), ABS (acrilonitril - butadiene - styrene), etc.

• Group B: $0,35 < ß < 0,55 cm^{-1}$, plastic materials which can be welded in good conditions by ultrasounds. Within this group are PP (polipropilene), PVC.

• Group C: $ß > 0,55 cm^{-1}$, soft plastic materials which can be welded very difficult using ultrasounds, resistance of the weldings is generally low. Within this group are PE (polyethylene), PA (polyamide).

The ultrasonic welding parameters of plastics materials define the welding quality, which is determined by the basic parameters of the process which directly influence the size of transmitted and absorbed energy in welding place. In the group of basic parameters are included: the oscillations amplitude of the active part of sonotrode, frequency of the ultrasonic oscillations, welding time, statically pressure in the welding area and the intensity of the ultrasonic energy.

In the group of auxiliary parameters of the ultrasonic welding make part the followings: dimensions, shape and material of the sonotrode and of anvil, shape factor of the concentrator and of sonotrode, reflexion and absorption quality of the anvil, and the previous heating temperature of sonotrode. The optimum welding regime (which depends on welding material, thickness and shape of pieces) can be determined only by experimental tests corresponding to the established purpose.

Oscillations amplitude represents the parameter which determined the energy level of the radiation transmitted into the welding area, elimination of the impurity particles, local heating and finally the welding quality. The resistance of welding increases in the same time with amplitude, the maximum value of this will be limited by the possibility to damage or deforming of the contact area between material and sonotrode.

In order to decrease the welding time and to obtain a good quality joining it is necessary a preliminary projection of the surfaced which must be welded, according to the joint type, provisioning ultrasonic concentrators, represented in the Figure 3.

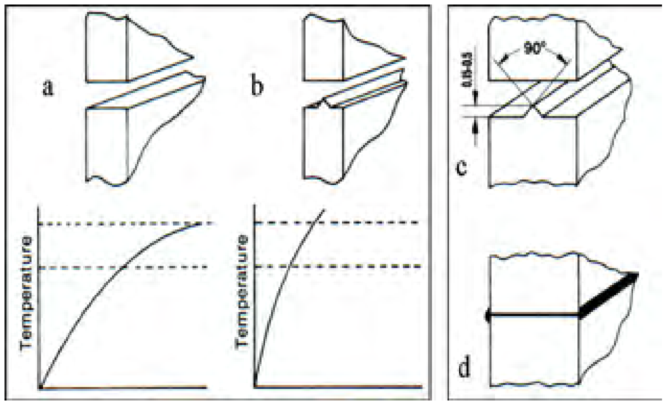


Figure 3. Influence of concentrator upon the welding process:
a - Welding in near field, by contact; b - Welding in far field, by transmission.

The purpose of the concentrators is to concentrate and direct the ultrasonic energy in the joining area and determine a fast plastic flow of material from the concentrator volume in the joining area. In order to weld recipients under pressure made by crystalline plastic materials, in condition of air-tightness, it must follow the geometry presented in the Figure 4. The elements which describe the geometry of joining take the following values: e = 1...3,5mm; x= e/5 ... e/6 mm, a= 0,45e.

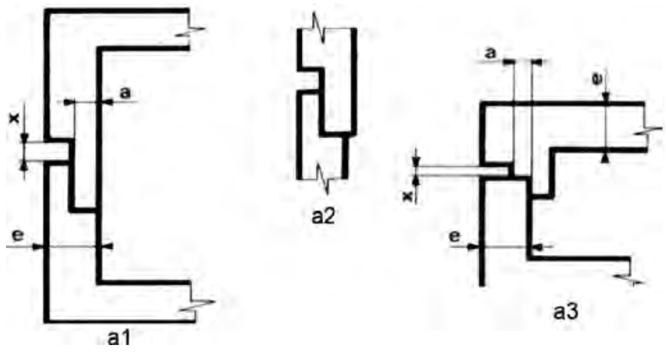


Figure 4. Concentrator type for contour welding
a1 - classic; a2 - with thin walls;
a3 - with high pressure from inside.

In the processing of the joining boundaries must be keeping in view an appropriate adjustment in order to permit the vibrations transmutation as well as a sufficient space necessary for flowing of the melted plastic material. It is recommended to weld the plastic materials with amorphous structure (polystyrene, polycarbonate and acryl-nitride-butadiene-styrene) using concentrators with V shape. The elements which describe the geometry of joining take the following values: e= 1...3,5 mm; x= e/5 ... e/6 mm.

2. Ultrasonic joining by thermoplastic deformation - riveting

One of the applications studied within this paper is the riveting process of plastic materials with other materials, using ultrasounds. This method has many advantages comparing with classic method with hot coin: the obtained joint is without tensions, it has a high capacity of stress, high resistant to the temperature variations and the execution time is very short.

For riveting is used the same principle of transformation of ultrasonic energy in heat, but in contrast with classic welding, this transformation is between the sonotrode and surface of plastic material. The active surface of sonotrode is proper to the final geometry of the rivet head.

The developed heat together with welding-pressure force determines the thermoplastic deformation in the material volume. The shape of head rivet in ultrasonic riveting process is presented in the Figure 5.

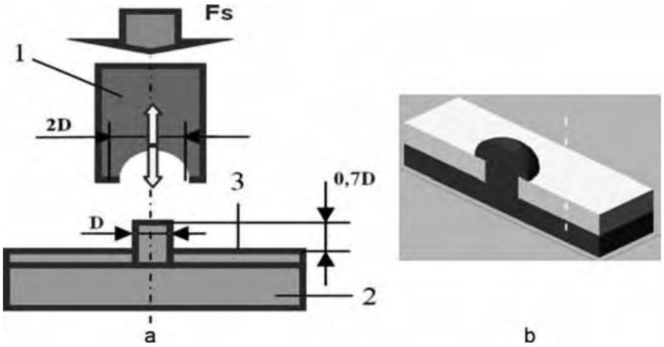


Figure 5. Head shape in the ultrasonic riveting
a - before welding; b -after welding.

When is necessary multiple riveting, or for increasing the productivity it can be used specialized sonotrode with multiple active elements, or specialized constructions with multiple sonotrodes, presented in the Figure 6.

Figure 6. Sonotrode for multiple riveting
a – sonotrode with multiple active elements;
b – welding head with multiple sonotrodes.

The activities of technological transfer were based on special programs for technological experiments using specialized welding equipments with ultrasounds for industrial applications. In the Figure 7 it is presented an welding equipment for plastic materials joining composed by a generator and command system in programmed techniques (3), a specialized sonotrode with 4 active elements (1) and the device for positioning in the welding process (2), developed at ISIM Timișoara, and use in qualifications programs of welding technologies.

This equipment is destined to the ultrasonic welding by thermoplastic deformations of four rivets from polyamide (6-6 with 30% glass fibers) with metallic shield OL37 used in the component of structure and in configuration of micro-motors for the plastic materials used in automotive industry and in electrotechnique industry – with the goal to obtain high welding technologies and realize the alignment to the European standards and norms.

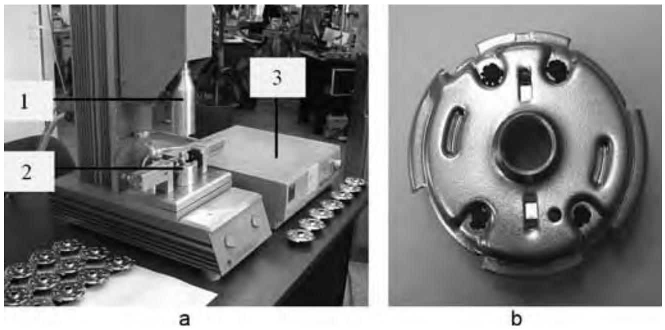


Figure 7. Ultrasonic welding of plastic materials
a - welding equipment; b - rivet welding.

Experimental programs for this application require development and software simulation of the tools, specialized sonotrodes and the setting of devices for welding. Determination of the initial conditions regarding the material quality in the process of sonotrode manufacturing required utilization of the laboratory equipments, in order to investigate the quality of the internal structure of materials – nondestructive control and determination of the sound velocity in the materials. Sound velocity through the material represents the essential technological parameter in the simulations programs regarding the geometry of sonotrode configuration.

Simulation with a specialized program allows knowing the stress parameters of sonotrode, the horn gain coefficient, nods and loops positions, the amplitude size, resonator amplitude, the curves of strain energy and also the curves of internal resonator stress of sonotrode. The shape and the sizes of the interface system with the attachment elements – buster or piezoceramic convertor were defined.

In the Figure 8 is presented a diagram of variations curve of the internal stress (fig. 8a) and resonator amplitude (fig. 8b) of the sonotrode with 4 active elements which is used for ultrasonic welding by thermoplastic deformations of four rivet s by polyamide (6-6 with 30% glass fibers brush-collar carcass) with OL37 metallic shield, resulted during the simulation process. For the final calibration it was used an experimental stand of measurement formed by a signal generator and an oscilloscope with memory.

Characteristics elements of the sonotrode, used in the experimental program are presented in the Table 1.

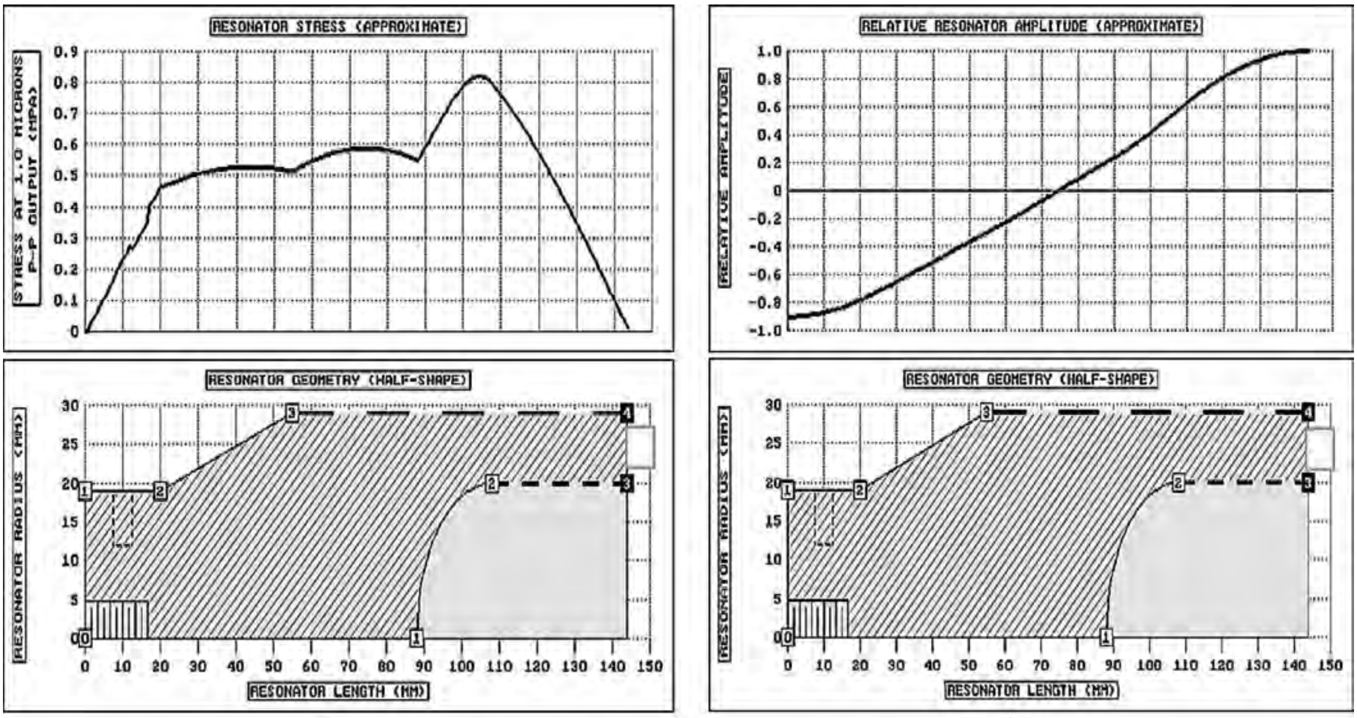
Devising for welding of the singular piece brush-collar support made from polycarbonate and OL37 metallic shield, presented in Figure 9, has solved the next essential aspects of the welding operation:

- Reciprocal geometry position of the samples;
- Piece positioning by static clamping force metallic shield – brush collars;
- Acoustic isolation of welding workpieces in relation with positioning device;

• Acoustic isolation of welding workpiece related to the fixture clamping device metallic shield – brush collar;

• Opto-electronic sensor which indicates the presence of workpiece for the welding process.

amplitude of ultrasonic oscillations 44.4μm, were assured with reproducibility by the command and control systems of special welding equipment.



a b

Figure 8. Software simulation of sonotrode with 4 active elements.

Table 1. Characteristics elements of the sonotrode.

Material type	AlMgSi
Sound velocity [m/s]	4850
Sonotrode length [mm]	143.9
Resonant frequency [kHz]	20
Horn gain	1.11
Maximum stress MPa/mm	0.82 /104.5
Coordinate of oscillation Node [mm]	74.5
Dissipated power[Watt]	6.5 10^{-4}

Figure 9. Welding fixtures
1- alignment element; 2 - fixture and acoustic isolation device; 3 - acoustic isolation; 4 - sensor; 5 - sonotrode with 4 active elements.

Technologic parameters for welding: static clamping force 80daN, welding time 1.2s, holding time after welding 1.5s,

Quality of joints was certificated by visual control, dimensional control of the rivet and by assuring that exist a good adjustment between the two workpieces (carcass - brush collar), with metallic shield from OL37.

3. Hybrid device of welding of reservoir with technological fluids from polyamide

Another ultrasonic application in the automotive industry developed within the institute ISIM had in view to realize an welding technology as an alternative to the joining technologies by soldering with chemical adhesives of vessels for technological liquids.

The classical welding process based on chemical adhesives was defective in two ways: efficiency and quality. Distinct components wetted at the interface with specific solvents are held in reciprocal position for a time necessary to adhesives drying by 48 hours. The results of quality verification using the tightness probe at the pressure of 3 bar shown a great number of inappropriate products, which presented damages like lack of tightness and breaking out of the two components in the welding plane with adhesive at a pressure lower than the 3 bar pressure.

Alternative solutions to adhesive joining can be: friction welding by rotation, ultrasonic welding and hybrid welding.

Critical analysis of these technological variants put in evidence in the case of friction welding by rotation the necessity of new and expensive equipment. In the case of ultrasonic welding is necessary to have a welding equipment of high power between 2500 – 3000W that is expensive too, and involve the necessity to change the injection dies for the two components to be jointed in order to create acoustic concentrators of energy at the interface between components.

The alternative solution for joining in condition of maximum economical and technological efficiency involved the using of the effects produced by the ultrasonic energy: spaying – atomization of the liquids existing on the ultrasonically activated surfaces, the ultrasonic cavitations and the heating effect.

The new proposed and tested technology proposed to maintain the different components without the necessity to realize constructive changes.

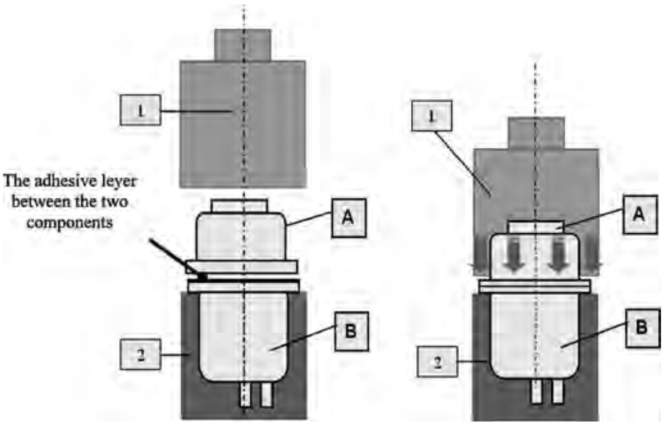


Figure 10. Hybrid welding scheme – adhesive with US
1 - sonotrode; 2 - B fixing device.

The welding experimental program use an ultrasonic welding equipment by low power 400W, 20KHz equipped with a specific sonotrode for the configuration of the A component and positioning device for the B component.

Experimental programs for this application imposed the development and software simulation of special sonotrodes, as well as a resolution of the welding device.

The simulation with specialized programs allows the knowledge of state parameters of the sonotrode, resonator gain, node position, amplitude, variation curves for loss and internal stress of sonotrode. There were defined the shapes and dimensions of the interconnection elements with coupling elements - booster and piezoceramic converter.

In the Figure 11 is presented the variation curve of the internal stress (fig. 11a) and amplitude diagram (fig. 11b) of a specialized sonotrode for ultrasonic welding by a hybrid process of the vessels with technological liquids from polyamide, as a result of the simulation program.

Characteristics elements of the sonotrode used in the experimental program are presented in the table 2.

Table 2. Characteristics elements of the sonotrode used in the experimental program.

Material Type	AlMgSi
Sounds velocity [m/s]	4850
Sonotrode lenght[mm]	158.1
Resonance frequency [kHz]	20
Horn gain	2.37
Maximum stress MPa/mm	0.73 /121
Coordinate of oscillation node [mm]	82.5
Dissipated power [Watt]	$9.4x10^{-4}$

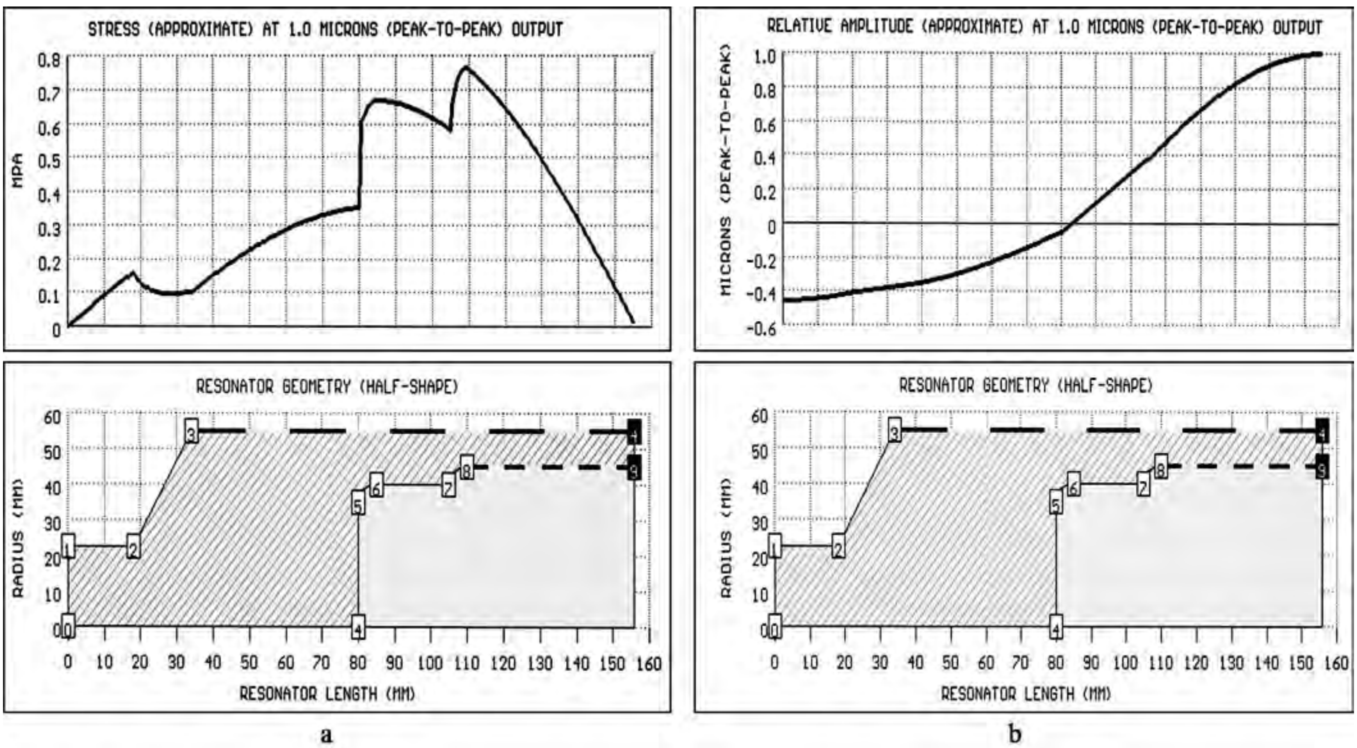


Figure 11. Sonotrode simulations for contour welding.

The hybrid welding operation device presented in the Figure 10 have in view the components loading on the specialized device, during the welding, with wetted interface using specific solvents.

In order to obtain an appropriate welding of the liquid vessel, presented in the figure 12, we used the following welding technological parameters: welding force 15daN, welding time

3.2s, maintenance time after welding 2,5s, ultrasonic amplitude of the oscillation 47,5µm, which were assured with repeatability by the command and control systems of the welding equipment. In the Figure 12a are presented the two components before joining, and in the figure 12b are presented the two components which form the reservoir, obtained by joining.

a b

Figure 12. Hybrid joint – liquid reservoir.

The quality of joining was realized by visual control, and by testing to tightness and pressure. The obtained products were 100% insulated and they were cracked outside of the joining plain at a pressure by 7 bars.

4. Conclusions

The usage of a specialized sonotrode with 4 actives elements led to obtaining of the assembly trailers carcass with metallic buckler of OL37 after a single transit, and implicit to a higher productivity than in the classical case of using only one heated element.

Quality of the joints realized by riveting welding was assessed by visual control, dimensional control of the realized rivet tip and by the lack of the backlash between the two components trailers carcass with metallic buckler of OL37.

For the component "recipient for technological liquids" after assessment of tightness and pressure, it was determined that this was 100% insulated and the crackers appeared outside of the joining surface at a pressure by 7 bar, much higher than the used pressure of 3 bar.

We can say that the hybrid welding process by ultrasonic activation of the interface by wetted with chemical solvent represents the optimal solution for the joining of the two components which form the recipient for technological liquids.

As well, the productivity and quality of the products obtained by ultrasonic welding are categorical superior to those obtained by the classical joining technologies and they are recommended for the automotive industry.

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Prof. Stojan Sedmak, professor of the University of Belgrade, Serbia, internationally recognized scientist, has died on 2.11.2014, at the age of 85. Ever since his post graduate Magister diploma work in 1968 he has been active in the field of Fracture Mechanics and Structural Integrity, introducing these disciplines in ex-Yugoslavia and Southeast Europe. His doctoral thesis, defended in 1977, was one of the first in the region to be completely devoted to fracture mechanics, leading to the establishment of a sound basis for its further development.

Based on that, Stojan has established International Fracture Mechanics Summer Schools, starting from 1980 (10 of then held in the meantime), and became the principle investigator of the USA-Yu project on "Weldment Fracture Mechanics", 1982-1990. These two activities were the pillars of strong development of Fracture Mechanics in the whole region, including all six ex-Yu republics. This was also the decade in which Stojan started his fruitful activities in the scope of EGF and European Conferences on Fracture, which culminated in 1992, with ECF9 in Varna, which he organized successfully as the "mission impossible".

Unfortunately, a tragic chain of events in ex-Yugoslavia significantly slowed down all activities afterwards. Anyhow, after 2001 a new era emerged, starting with the establishment of the Society for Structural Integrity and Life (DIVK) in Serbia, which has gathered more than 200 members, including 50 members of ESIS. Stojan served as the first president and the first editor-in-chief of the Journal "Structural Integrity and Life", also established in 2001. Renewed activities culminated with a successful bid for ECF22 to be held in Serbia in 2018, as decided in Trondheim in July 2014. Stojan has also witnessed another great recognition for Serbia - the president of DIVK becoming an ESIS Vice-President. Surely, to his greatest satisfaction, it was his own son, and if I may say, his loyal co-worker for the last 32 years. Let me be clear - there is no doubt it is he who should be honored for these two significant achievements and recognitions for Serbia and the region.

Now, when I look back at my father's career, I can see a great man with a vision, building the pyramid of knowledge, seeing everything from the top of it, and leading us all. I can see the raising pyramid touching the sky, taking him to well-deserved peace in heaven.

Belgrade, 4.11.2014 Prof. Aleksandar Sedmak
President of DIVK, Vice-president of ESIS