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Contributions for Setting the Technological Parameters in Ultrasonic Welding Process of Intelligent Composites with Polymeric Matrix

The paper describes the parameters in ultrasonic welding process of intelligent composites with polymeric matrix. Process parameters are divided in three different categories: technological parameters, mechanical parameters and acoustical parameters. Technological parameters are given special attention, and their influence on welding quality is analyzed.

1. Introduction

Making pieces from intelligent composites using ultrasonic welding process is a complex method because we have to take into account a series of elements linked to composite materials processing and also the technological, mechanical and acoustical parameters influencing the welding process.

Main elements that we have to take into account regarding the intelligent composite materials processing are: composition of materials forming the intelligent composites, matrix composition, reinforcing elements, sensors or sensors’ network used, geometry and overall dimensions of surfaces for welding, properties for each element forming composite materials and properties of the whole assemblage, fabrication process of composite materials, required productivity.

Main technological parameters of the ultrasonic welding process are: matrix class, reinforcing elements class, materials thicknesses, and conditions required by material functionality, welding method, acoustic energy concentrators number etc.

Acoustical parameters are linked to the ultraacoustic system and to the ultrasonic welding equipment and they are: ultrasonic oscillation type; oscillations amplitude; oscillations frequency; ultrasonic energy intensit; ultraacoustic energy density; dimensions, shapes and materials from which the sonotrode and acoustic anvil are built; ultrasonic energy concentrator’s form factor; absorption and reflexion properties of bearing; pre-heating temperature of the sonotrode etc.

Mechanical parameters having significant influence on welding process are: static pressure force, local-static contact pressure, ultrasonic activation time etc.

In most cases, for discovering the parameters influence on ultrasonic welding process means the determination of breaking load through shearing and stretching experiments, angled with 45° and 90° from welding direction. Reproducing the weld quality is made with coefficient of variation k_v, given by:

$$k_v = \frac{\sigma_m}{N_m} \cdot 100 \quad [\%] \qquad (1)$$

σ_m is medium square deviation at shearing and stretching stresses; N_m – arithmetic mean value at shearing and stretching stresses, determined with the following relation:

$$N_m = \frac{1}{n} \cdot \sum_{i=1}^{n} N_i \qquad (2)$$

n is individual measurements number; N_i – individual measurements value.

Medium square deviation σ_m is determined with relation:

$$\sigma_m = \frac{\sum_{i=1}^{n} \left(N_m - N_i\right)^2}{n-1} \qquad (3)$$

and its value is important because the significance level is ± 1,5%.

2. Influence of Technological Parameters on Ultrasonic Welding Quality

Technological parameters have a direct influence on shape, dimensions and characteristics of weld in conformity with the piece functional role.

Experimental results showed that the weldability of an intelligent composite material depends, in the first place, on coefficient of elasticity and on its' components hardness. It was ascertained that the higher coefficient of elasticity is, the smaller interior losses are, resulting in good ultrasonic energy trasfer to welding zone and high efficiency welding. It was also found that intelligent composite welding depends essentially on: melting or vitrification temperature, shock resistance, coefficient of elasticity, surfaces coefficient of friction and thermal conductibility.

For determination of a material welding behaviour, Silin, Baladin and Kogan criterion was taken into consideration in case of a random material k_r, resulting the formula:

$$k_r = \frac{\sigma_c^0}{\sigma_c^s} \cdot 100 \qquad [\%] \qquad (4)$$

σ_c^o is yield point at ambient temperature; σ_c^s - yield point at pieces' temperature.

When k_r = 0,3...0,25, we have proper weld abilities (weld ability decreases when k_r increases).

Sensors don't have any influence on the welding parameters or on the welding quality. Sensors distribution network must be designed in such a way so it won't be affected or interrupted during welding process, sensors distribution network defining the intelligent property of the composite material. When designing a piece is important to know the sensors network distribution so the piece functional role is maintained and the network continuity is not affected.

The sensor role is to attract information from the environment he is situated in. These information are transmitted to the actuator after they were interpreted by the control system and the actuator acts in conformity to it's program producing changes in the system. There are several types of sensors: optic fiber sensors, magnetic wires, piezoelectric sensors, temperature sensors, pressure sensors etc.

Optic fiber sensors can be divided into:

- *polarization, frequency, phase and intensity sensors,* all based on modulation and demodulation process. The ones used for determining the phase or frequencies are called interferometrics and the interferometrical technique means the coherent and heterodine detection;

- *physical, chemical and biomedical sensors* which are related to their aplications : for measuring temperature, voltage, pressure etc (physical sensors); for measuring the pH level, for gases analysis, for spectroscopical studies etc. (chemical sensors); for measuring blood pressure, glucose level, urine level etc. (biomedical sensors);

- *extrinsic sensors*, which test the fiber from the outside, and the fiber transmitts information to the measuring area and into desired shape;

- *intrinsic sensors* are sensors in which proper modification of one or more physical properties of the fiber takes place;

An optic fiber sensor is mainly made of: a light source, the optic fiber (with a certain detection and transmission length), a photodetector, demodulations, optical indicator and necessary electronic elements.

Sensors with magnetic wires are used to measure strains in composite materials (deformation sensors) and have at basis a very slim wire covered with a magnetic coating which has a significant alternance component. Control capacity of magnetic coatings applied on slim wires allows them to be applied in monitoring the polymeric composites fabrication process, and also in obtaining data regarding their behavior during exploitation.

Thermal sensors are based on Peltier effect and they are used to generate a thermal gradient for controlling the dynamic answer of a flexible structure. Such a temperature variation sensitive system is the thermoelement. The choice of a thermoelement depends on the maximum temperature that will be measured (Table 1).

Thermoelements can be used for monitoring the raisin cross line temperature during composite materials processing.

Actuators used for intelligent structures have to be able to read the system input data and transform it into physical units, causing system modification. An actuator frequently receives an electric signal which is converted into a deformation or a shifting. An actuator has: to be small enough to be included in the composite material during its' processing; to be cheap, to consume as little energy as possible and must not have important influence over structure integrity.

Table 1. Building temperatures for different types of thermoelements
(Marlin Manufacturing)

Crt. no.	Materials for thermoelement wires	ANSTI type	Temperature domains [°C]
1.	Copper-constantan	T	116...345
2.	Iron-constantan	J	0...760
3.	Chrome-alumel	K	0...1260
4.	Chrome-constantan	E	0...870
5.	Platinum-platinum-radium	N	0...1400

Most frequently used materials for building actuators are:

- piezoelectric materials (piezoceramics, piezopolymers etc).;
- constrictive materials (magnetostrictive, electrostrictive etc.);
- memory form alloys;
- electroreological fluids (delicate particle suspenses, semiconductors, into a dielectric fluid)

Table 2 shows some characteristics of materials used for bulding actuators and table 3 shows a relative estimation of different actuators used on intelligent structures.

Table 2. Technical characteristics of different actuators used on intelligent structures

Actuator name	**Material type**	**Characteristics**						
		Density [g/cm^3]	Hardness [Mpa]	Resistance [Mpa]	Deformation [%]	Frequency domain [Hz] (up to)	Temperature domains [°C]	Necessary energy consumption
Piezoelectric materials	Piezoelectric crystals	-	-	-	-	-	-	low
	Piezoelectric ceramics	7,5	65,000	75,000	0,20	20,000	200	medium
	Piezoelectric polymers	1,8	2,000	150	0,06	100,000	100	high
	Piezoelectric fibers	-	-	-	-	-	-	medium
Constrictive ceramic materials	Strictive devices type E	8	48,000	2	0,12	20,000	200	low
	Strictive devices type B	9,25	30,000	28	0,20	20,000	0-380	high

The evaluation has taken 5 factors into account:

- level of performance – evaluated by considering final values of amplitude and frequency, and also considering the requirements regarding energy consumption;

- weight – includes the disadvantage of peripheral weight necessary for operating specific alternate actuator (e.g. weight associated with producing and maintaining the magnetic field for magnostrictive devices);

- operation simplicity - information transformation degree (volume modifying) and relative stress needed by the actuator;

- execution easiness – the evaluation of difficulty level when introducing the actuator in the intelligent composite mass doesn't represent a clue regarding the making of the transducer;

Table 3. Relative options comparison for actuators used on intelligent structures

Actuator name	**Material type**	**Characteristics**					
		Perfor mances (5=high)	Weight (5=easy)	Handling (5=easy)	Execution (5=simple)	Cost (5=cheap)	Total
Piezo electric materials	Piezoelectric crystals	4	3	5	1	2	15
	Piezoelectric ceramics	4	4	5	3	3	19
	Piezoelectric polymers	3	4	5	3	3	18
	Piezoelectric fibers	4	3	3	3	2	15
Constrictive ceramic materials	Strictive devices type E	5	4	4	3	3	19
	Strictive devices type B	3	2	3	2	3	13
Memory form alloys	Alloys with NiTi	4	4	3	5	2	18
ER fluids		3	2	2	2	3	12

- cost – is established in accordance to the quantity.

From table 3 can be noticed that piezoelectrical ceramics and strictive devices type E are optimal actuators choices for usage. Order of preferences regarding the two types of materials depends on factors like dependence of hysteresis and temperature, factors that have not been evaluated in the present paper.

Experimental research using optic fiber sensors or piezoceramic plates showed that if these are included in welding zone, surface deterioration of optic fiber or debias of piezoceramic plates will appear resulting in sensor properties loss.

The profilogram has an important influence, because each microirregularity of the surface is an acoustic energy concentrator meaning the melting will first appear in points number 3, points of greatest height (figure 2). Melted material (4) is pushed out in microdepths of the inferior surface, this contributing to melting the other microirregularities, process intensified by ultrasonic energy from welding zone.

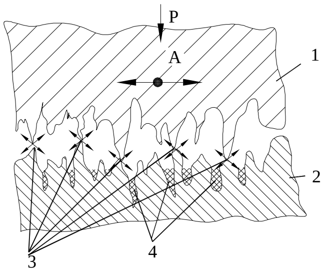

Figure 1. The profilogram of contact surfaces:1, 2 – contact surfaces; 3 – first contact microirregularities; 4 – melted material;P - static pressure force; A –ultrasonic oscillations amplitude.

Research made showed that the bigger the microirregularities are, the easier the welding process is and joint has a better quality.

Ultrasonic welding process can be divided, coventionally, in two stages:

- on the first stage, ultrasonic oscillations provoke heat developement on contact microirregularities on the two surfaces. These microirregularities have a relative movement to one another with an ultrasonic frequency and an amplitude (A), resulting a great amount of heat. Most thermoplastic materials melt in a very short time;
- on the second stage, between contact surfaces, heated untill plastic state temperature is reached, appear connections which allow the forming of a resisting weld, only after microirregularities have melted and created a homogenize zone.

Welding method has important influence on weld quality because related to it takes place the ultrasonic energy repartition in the microirregularities of surfaces, dosing ultrasonic energy and the degree of continuity and mechanization of welding process.

Two welding methods are used regarding the criteria of repartition and dosage of the ultrasonic energy in the welding zone:

- near field welding or contact ultrasonic welding, in which case the sonotrode is brought as close as possible to welding zone (fig. 2a). In this case, ultrasonic energy is uniform alloted on surfaces of pieces for welding (1 and 2). The front side of the sonotrode which takes contact with the superior piece, has the same shape as the pieces. the method is used for plastic materials such as: polyethylene, plastified PVC and others with thicknesses less than 6 mm, resulting lap joints welding structures.

- far field welding, when ultrasonic oscillations apply in a certain point or on a small surface of the superior piece (fig. 2b), and the welding process takes place in an area which is situated further from the sonotrode. Uniform transmission and repartition of ultrasonic energy is linked to materials' capacity of transmitting mechanical vibrations, that is why far field welding method is used for hard plastic materials such as: polystyrene, polycarbonate, ABS etc. Most used is the butt joint welding type.

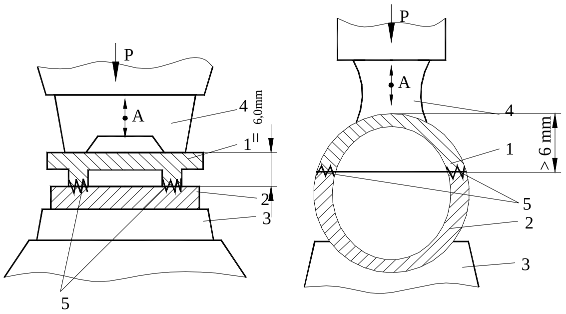

Figure 2. Ultrasonic welding methods of intelligent composites:A – near field welding; b –far field welding : 1 – superior piece; 2 – inferior piece; 3 – acoustic anvil;4- sonotrode; 5 – welding zone.

In the end we can conclude that ultrasonic welding of intelligent composites is a complex process because we have to take into account the elements linked to processing the intelligent composites and also technological, mechanical and acoustical parameters all with different influence on welding process.

Beside the mentioned parameters, building pieces from intelligent composites also depends on other technological parameters such as: sonotrode's chemical compositions, surface quality in sonotrode contact zone, surface cleaning state in welding zone, acoustic anvil material composition, surfaces quality of acoustic anvil, environmental conditions when welding etc.

3. Acoustic Conditions Influence On Weld Forming

One of the factors determining the weld quality is the apearance and development of plastic deformation in materials, over which acoustic conditions have an important influence.

Different acoustic oscillations can be produced by different material oscillations, and they are: longitudinal oscillations, shearing oscillations, bending oscillations, torsion oscillations and combined oscillations, whose excitation in the welding zone is made by specific designing, construction and execution of the ultraacoustic systems used in purpose for creating and propagating ultrasonic oscillations.

Experimental research showed that by exciting longitudinal waves in the sonotrode, made through calculations of the ultraacoustic system with longitudinal waves working at resonance, the weld resistance and the variation coefficient k_v both depend on the sonotrode's length and the spot where static pressure force is applied.

Weld quality, when weld is obtained by systems in which bending oscillations are excited and propagated, is lower than the one obtained through longitudinal waves, because of system feed-point impedance large variation at self-regulation frequency.

Experimental results on polymeric matrix composites revealed that the most efficient ultraacoustic systems are those in which shearing and longitudinal-transverse oscillations are excited and propagated, because these ensure a good destruction and removal of oxides from the welding zone, they seal the weld and do not allow oxigen access, they produce complex displacements of the material in the contact zone and they create proper conditions to weld forming.

4. Influence of Ultrasonic Oscillations Amplitude on Weld Quality

Weld forming with ultrasonic oscillations help depends on sonotrode's oscillations amplitude A_s and on static pressure force P_s. Oscillations from sonotrode 1 are transmitted to materials 2 and 3 (fig. 3) and to the acoustic anvil 4, each vibrating with corresponding amplitudes, with the condition:

$$A_s > A_{ps} > A_{pi} > A_n \qquad (5)$$

Between sonotrode and superior piece there is a force F_s, with following formula:

$$F_s = A_s \sin \omega t \qquad (6)$$

and between piece 2 and piece 3, we have the friction force F_f, defined by:

$$F_f = A_s \sin \omega t \qquad (7)$$

and static pressure force P_s.

Relation between the two forces is:

$$F_f \leq \mu P_s \qquad (8)$$

As long as $F_f \leq \mu P_s$, the two materials oscillate without edging, the edging apearing only when $F_f > P_s$ and when energy loss ΔE is at its highest level (fig.4). Experimentally was determined an optimum value for static pressure force $P_{s\ opt}$ with formula:

$$P_{s\ opt} = S_c \cdot \sigma_c{}^{o} \qquad (9)$$

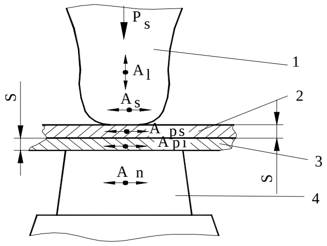

Figure 3. Vibration scheme when ultrasonic welding the intelligent composites with polymeric matrix: 1- sonotrode; 2 – superior piece; 3 – inferior piece; 4 – acoustic anvil.

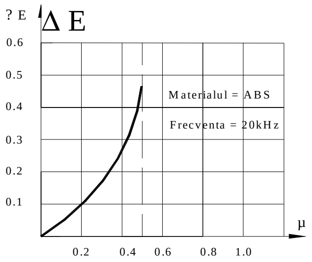

Figure 4. Energy loss ΔE, depending on coefficient of dry friction μ, at 20kHz frequency.

S_c - contact surface of sonotrode with the superior piece; $\sigma_c{}^o$- material yield point at reference temperature of 20°C.

Knowing the optimal pressure force we can determine optimum sonotrode's amplitude, regarding the optimal tangential force $P_{t\,opt}$, which has the following formula:

$$P_{t\,opt} = k \cdot \mu \cdot P_{sopt} \qquad (10)$$

and leads to displacement tensions in welding zone τ_f, having the next formula:

$$\tau_f = \tau_x \cdot \sin \omega t \qquad (11)$$

Connection of τ_x, A_{ps} and A_{pi} is given by:

$$A_{ps} - A_{pi} = 10\frac{\tau_x}{G}h + k \qquad (12)$$

h – plastic deformation height zone; G – shearing modulus; τ_x – shearing yield point in welding zone with formula:

$$\tau_x = \tau_s \cdot \sqrt{1 - \left(\frac{mP_s}{3\pi a^2 \tau_s}\right)^2} \qquad (13)$$

where: m is a coefficient depending on sonotrode's construction (m = 0, 1, 2, 3,); τ_s- shearing yield point of sonotrode's material; a – coefficient depending on material thickness (a = 1...3s); s – pieces thicknesses.

For example, in case of intelligent composites with polymeric matrix, following optimal relations were established for optimal connection:

$$A_{ps} = 0,7\,A_s;\ A_{pi} = 0,4\,A_s;\ A_s = 3,3\left(10\frac{\tau_x}{G}h + k\right) \qquad (14)$$

Amplitude's influence on ultimate strength of ultrasonic welded structure can be seen in figure 5. It can be noticed that by reducing amplitude of ultrasonic vibrations, welding resistance F_r is also reduced, and for amplitude's values beneath a minimum $A_{s\,min}$, the joint doesn't take place.

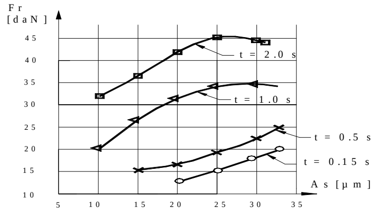

Figure 5. Sonotrode's amplitude influence on ultimate strength at different welding times.

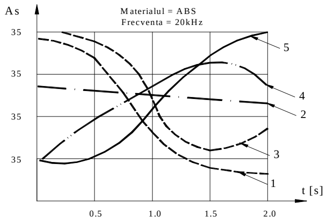

Figure 6. Amplitude variation A_s of sonotrode with time, at different oscillations types: 1 – longitudinal; 2 - shearing; 3 - bending; 4 - longitudinal-torsion; 5 – torsion.

Oscillation amplitude of the sonotrode's front part has influence on acoustic energy proportioning in the welding zone, which has to have a bigger value on the first stage of surfaces contact. After increasing the physical contact in the stage of interaction furnace forming between surfaces, oscillation amplitude has to be reduced at 50% to avoid breaking of previously made connections. At this stage, acoustic energy is spent for increasing plasticity and material melt processes in the welding zone.

Temperature increasing in the contact zone leads to increased thermal energy of atoms which favours material transfer process to existing micropores, instead of diffusion process. So amplitude variation of the two stages representing the weld form has to be as in figure 6, depending on excited oscillation type which is propagated in the sonotrode.

Sonotrode's amplitude variation with transducer's output power W_t is displayed in figure 7, where can be seen that as the output power increases, amplitude variation of the sonotrode increases in all cases.

Experimentally can be observed that mechanical resistance F_r of ultrasonic welded structures is optimal for a certain amplitude and a certain ultraacoustic system excitation (figure 8).

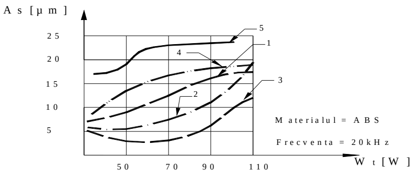

Figure 7. Amplitude variation A_s of the sonotrode with transducer output power W_t, for different types of oscillations:
1 - longitudinal; 2 - shearing;
3 - bending; 4 - longitudinal-torsion;
5 – torsion

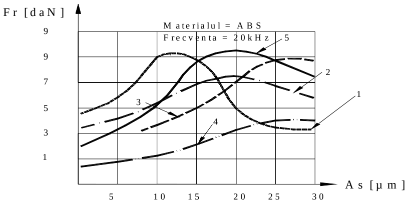

Figure 8. Ultimate strength variation F_r, of welded structure with ultrasonic oscillation amplitude of the sonotrode A_s, for different types of oscillations: 1 - longitudinal; 2 - shearing; 3 - bending; 4 - longitudinal-torsion; 5 – torsion

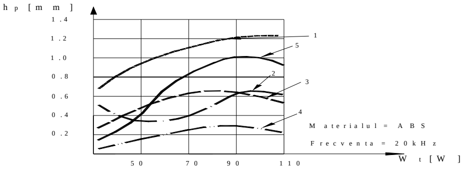

Figure 9. Edging depth variation h_p, with transducer output power W_t, for different types of oscillations: 1 -longitudinal; 2 - shearing; 3 - bending; 4 - longitudinal-torsion; 5 – torsion.

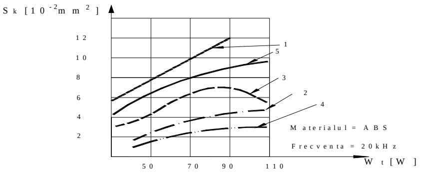

Figure 10. Contact surface variation S_k, with transducer output power W_t, for different types of oscillations: 1 - longitudinal; 2 - shearing;
3 - bending; 4 - longitudinal-torsion; 5 – torsion.

Contact surface S_k between contact micropores is increasing together with increasing transducer output power W_t (figure 9), which is obvious because thermal energy substantially increases after adding acoustic energy in the process. Micropores edging depth h_p increases almost in the same way, resulting the weld (figure 10).

4. Influence of Ultrasonic Oscillation Frequency on Welding Quality

Optimal frequency determination for ultrasonic welding of intelligent composite materials is made regarding oscillation amplitude, ultrasonic waves intensity, contact pressure, materials composition and thicknesses.

Experimentally was observed that ultrasounds intensity increases as oscillations amplitude decreases for a given output power of the transducer, which leads to conclusion that there is a certain working frequency for obtaining the best welding quality. Results of designed experiments show that the optimal frequency (figure 11), depending on material composition and transducer output power, is situated somewhere between 19kHz and 40kHz.

5. Influence of Acoustic Intensity on Welding Quality

The determination of an optimal acoustic intensity is a complex matter because it depends not only on the ultraacoustic system output power but on sonotrode's tip amplitude and oscillation type of the ultraacoustic system, weld shape, contact surfaces size and materials composition.

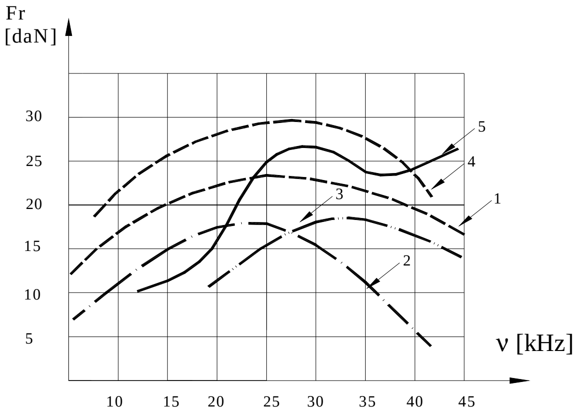

Figure 11. Ultimate strength variation of weld F_r, depending on ultrasounds frequecy ν, for different types of plastic materials:1- ABS; 2 – polystyrene; 3 – polycarbonate; 4 – vinile polychloride;5 – high density polyethylene.

Experimentally is observed that as the acoustic density increases, welding time decreases and ultimate strength of the material decreases (figure 12), explainable thing because in case of overcoming a certain value of acoustic density, thermal energy of welding zone increases and material starts to destroy itself.

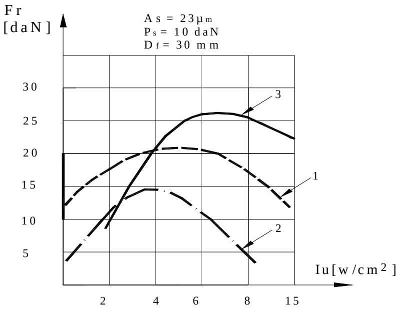

Figure 12. Ultimate strength variation of weld F_r with acoustic energy density I_s, for different types of plastic materials:1- ABS; 2 – high density polyethylen; 3 – polycarbonate.

The acoustic density influences the welding zone in different ways, depending on materials composition and weld overall dimensions. It can be noticed that there is always an optimum value of acoustic energy density depending on material composition, amplitude and static pressure force of the sonotrode in welding zone.

In the end we can conclude that ultrasonic welding of intelligent composites is a complex process, also depending on: sonotrode's compositions, surface quality in sonotrode contact zone, surface cleaning state in welding zone, acoustic anvil material composition, surfaces quality of acoustic anvil, environmental conditions when welding etc, parameters which have not been discussed in present paper.

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