Theoretical Studies of Processes And Apparatus For Ultrasonic Ring Welding of Thermoplastic Materials

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***Abstract* – The article is devoted to the discussion of the results of theoretical investigations of joining of polymeric materials by ultrasonic welding seam made by the ring-shaped working tool. According to results of theoretical studies optimal parameters are established according to the energy influence depending on the diameter and the width of formed weld. The theoretical results are allowed to propose an algorithm of optimal control of ultrasonic welding of thermoplastic materials in formation of circular welds of large diameter and to realize a new approach to the design and selection of specialized ultrasonic equipment.**

***Index Terms* – Vibrating system, circular weld, polymeric material, ultrasonic welding.**

I. INTRODUCTION

NOWADAYS POLYMERIC materials are applied in all industries. Due to their properties polymeric materials successfully replace traditional constructional materials such as steel, glass, ceramics, etc. In many cases the use of the polymeric materials can reduce the cost of products and simplify their production. Furthermore the polymer products have greater performance and can be used in a contact with corrosive environments, at low temperatures, under alternating mechanic loads, etc.

Almost in any area of the application of the polymeric materials providing of required strength of products is the main problem and it attracts a great number of researchers, engineers and designers. Particular interest presents by products, at which production it is necessary to ensure a tight and durable connection of circular weld (see Fig.1).

The most effective and reliable way to join polymeric materials is the ultrasonic weld. The diagram of the ultrasonic welding process of the parts is shown in Fig.2.

The method is widely used at the formation of seams with the tools of small size (much smaller than the wavelength) and is not practically used for the formation of the ring-shaped joints with length of generated seam (the perimeter of the tool) more than 200...300 mm. The reason of absence of specialized equipment for forming of ring-shaped joints of large diameter is the lack of information about the characteristics of the process of ultrasonic welding at the formation of ring-shaped welds.

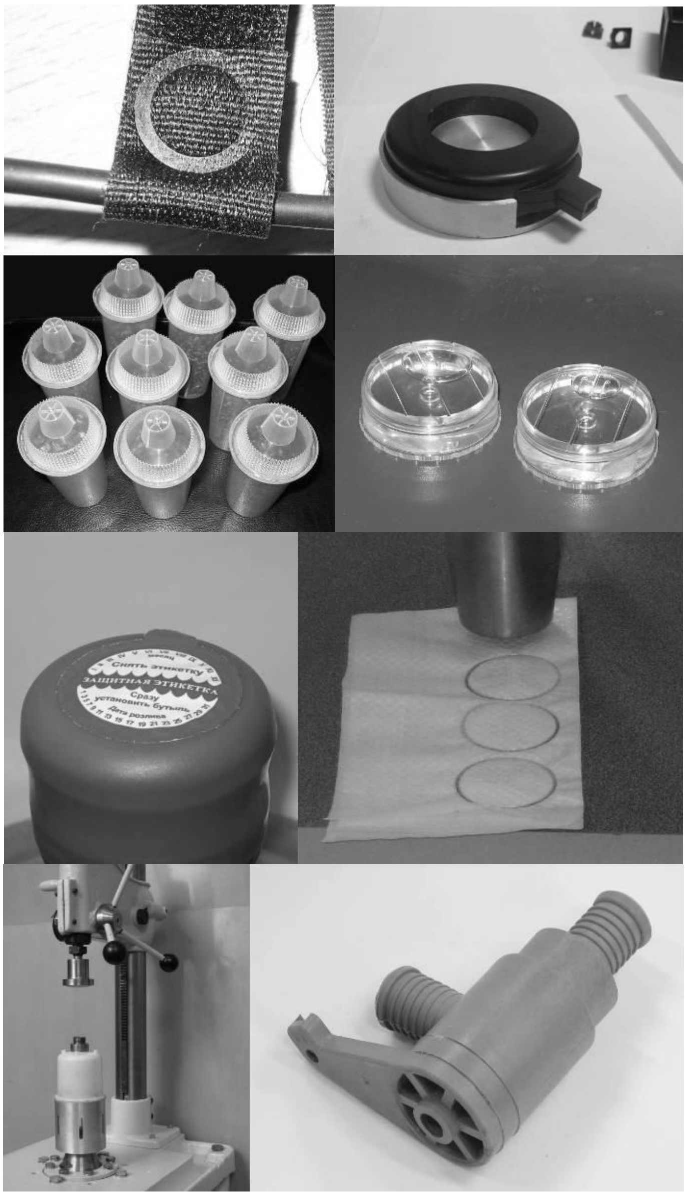


Fig. 1. Type of the samples with ring-shaped welds

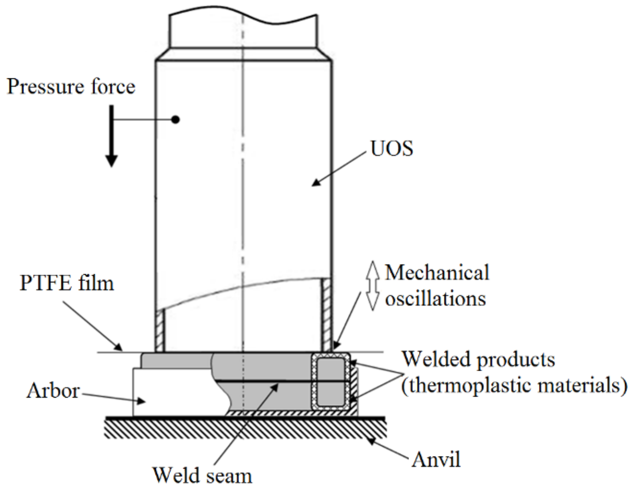


Fig. 2. Scheme of ultrasonic welding process

In this connection there is a need to study the mechanism of the formation and propagation of ultrasonic vibrations to welding seam in circular tubular structures for determination of optimal parameters of ultrasonic welding of polymeric materials of circular shape (expansion tanks, compasses, packaging, etc.).

II. PROBLEM STATEMENT

The mechanism of propagation of ultrasonic vibrations in circular tubular structures is important at the development of ultrasonic welding technology of such products. As in the antinodes of the mechanical stress the regions of overheating and polymer degradation usually appear. Polymeric materials with a narrow temperature range of welding are particularly sensitive to irregular ultrasonic field.

The analysis of modern requirements to the quality of formed ring-shaped joints at the manufacture of the products in the form of rotating body, and also a review of existing ultrasonic vibrating systems and existing specialized equipment for ring welding show almost complete absence of the methods for calculating of ultrasonic systems, which are suitable for the designing of the ring-shaped welding tools.

In this regard there is a necessity for theoretical researches of ultrasonic welding process with welding tool having a ring shaped end. The main objective is to develop a new approach to the design of the ultrasonic welding equipment.

Thus, to achieve the objective the following tasks were stated:

1. To carry out theoretical investigations of the welding process for the establishing of dependences of welding materials parameters and formed ring-shaped welding joint such as the diameter and the width of the seam with the energy released in the welding zone.

2. To detect change in the amount of emitted energy from the properties of welding materials and the geometric parameters of the welding tools (diameter and width of the seam).

3. To determine the optimal parameters of ultrasonic influence for different models of ultrasonic devices in the formation of various ring-shaped welding joints.

III. THEORY

Solving the first problem the theoretical studies of the welding process of ring-shaped weld were carried out (see Fig.3).

For the solution of the first problem it was determined the dependence of rate of ultrasonic energy dissipation:

Point 8 corresponds to the absorption zone of ultrasonic vibrations, heat emission and formation of the welded joint in the volume of welded materials limited by the surface area *S* and the thickness of materials 2*x*. Ultrasonic vibrations generated and amplified by the vibrating system are introduced at the boundary between the welding tool of the ultrasonic vibrating system and welded materials 5.

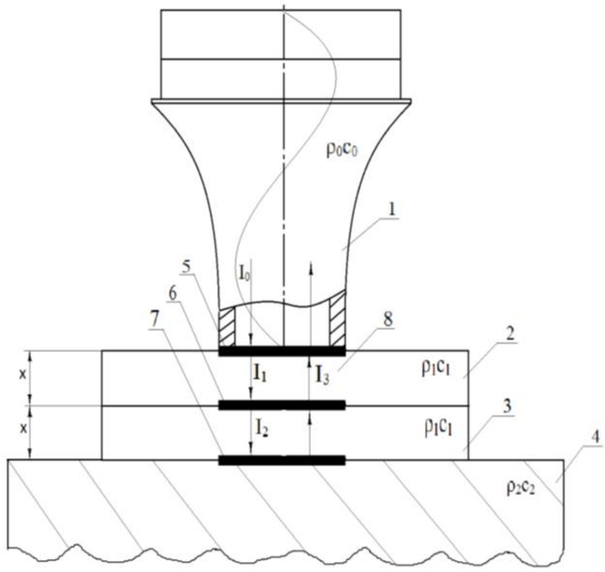


Fig. 3. Scheme of the ultrasonic welding process

The intensity of ultrasonic vibrations is generated on the radiating surface of the ultrasonic vibrating system:

$$I_0 = 2\pi^2 \cdot f^2 \cdot A_0^2 \cdot \rho_0 \cdot c_0 .$$

On the border 5 the reflection of the ultrasonic wave occurs, and a part of the ultrasonic vibrations passes through the border into the welding material 2. Wherein it is possible to determine reflection coefficient η and transmission coefficient of the wave *d* at the interface:

$$\eta_1 = \left(\frac{\rho_0 \cdot c_0 - \rho_1 \cdot c_1}{\rho_0 \cdot c_0 + \rho_1 \cdot c_1} \right)^2 ,$$

$$d = 1 - \eta_1 .$$

Then, in thermoplastic material 2 with the acoustic impedance $\rho_1 c_1$ the wave will be introduced with the intensity:

$$I_1 = 2\pi^2 \cdot f^2 \cdot A_0^2 \cdot \rho_0 \cdot c_0 \cdot \left(1 - \left(\frac{\rho_0 \cdot c_0 - \rho_1 \cdot c_1}{\rho_0 \cdot c_0 + \rho_1 \cdot c_1} \right)^2 \right) .$$

Energy absorbed by the thermoplastic material 2 can be calculated as follows:

$$W_1 = \left(I_1 - I_1 e^{-2\alpha x} \right) S,$$

where α is the attenuation coefficient of the amplitude, $I_1 e^{-2\alpha x}$ is the intensity of the ultrasonic vibrations at the interface 6, 2*x* is the path passed by the wave.

So as to ensure passing of more energy of ultrasonic vibrations across the border of welded materials it is necessary to provide the full acoustic contact, border 6 is represented as acoustically transparent and d=1. Then the intensity of the ultrasonic vibrations absorbed in the material 3 can be calculated as

$$I_2 = I_{1.} e^{-2\alpha x} - I_{1.} e^{-4\alpha x}.$$

Wave energy reflected from the boundaries of the "welded material–air" and the anvil 4 must be also taken into account to determine the energy absorbed by the material 3.

Then we can find the reflection coefficient η_2 and calculate the intensity of the wave reflected from the boundaries 7.

$$\eta_2 = \left(\frac{\rho_1 \cdot c_1 - \rho_2 \cdot c_2}{\rho_1 \cdot c_1 + \rho_2 \cdot c_2} \right)^2,$$

$$I_2 = \eta_2 \cdot I_{1.} \cdot e^{-4\alpha x}.$$

The intensity of the reflected energy absorbed by welding materials in the welding zone is:

$$I_{22} = \eta_2 \cdot I_{1.} \cdot e^{-4\alpha x} - \eta_2 \cdot I_{1.} \cdot e^{-8\alpha x}.$$

Then the intensity of ultrasonic vibrations and the energy absorbed in the material 3 taking into account of reflected wave energy is calculated as follows:

$$I_2 = I_1 \cdot e^{-2\alpha x} - I_1 \cdot e^{-4\alpha x} + \eta_2 \cdot I_{1.} \cdot e^{-4\alpha x} - \eta_2 \cdot I_{1.} \cdot e^{-8\alpha x},$$

$$W_2 = I_2 \cdot S,$$

$$W_2 = I_2 \cdot S = I_1 \cdot \left(- e^{-4\alpha x} + \eta_2 \cdot e^{-4\alpha x} - \eta_2 \cdot I_{1.} \cdot e^{-8\alpha x} \right) \pi \cdot (h \cdot D + h^2).$$

Then the total rate of energy dissipation of the ultrasonic vibrations in welded materials will be obtained:

$$W = 2\pi^3 \cdot f^2 \cdot A_0^2 \cdot (h \cdot D + h^2) \cdot \rho_0 \cdot c_0 \times \times \left(-\eta_2 \right) \left(- e^{-4\alpha x} + \eta_2 \cdot e^{-4\alpha x} - \eta_2 \cdot I_{1.} \cdot e^{-8\alpha x} \right),$$

where I_0 is the intensity of the ultrasonic vibrations on the radiating surface of the ultrasonic vibrating system; f is the vibration frequency of the tool; A_0 is the amplitude of the ultrasonic vibration tool; η_1 is the reflection coefficient from the material 2; η_2 is the reflection coefficient from the boundary 7; d is the transmission coefficient; $\rho_0 c_0$, $\rho_1 c_1$, $\rho_2 c_2$ is the acoustic impedance; I_1 is the intensity of ultrasonic vibrations in the material 2; W_1 is the energy absorbed by the thermoplastic material 2; α is the amplitude attenuation coefficient; $2x$ is the path passed by the wave; S is the surface area of the absorption of ultrasonic vibrations; I_2 is the intensity of ultrasonic vibrations in the material 3; I_3 is the intensity of the reflected energy absorbed by 2 and 3 in the zone 6; W_2 is the energy absorbed in the material 3; W is the total energy absorbed by the medium 8; D, h are the outer diameter and the width of the ring of the ultrasonic tool. Obtained expression allows setting up the time dependence of ultrasonic influence for the formation of welded joint on the energy of ultrasonic vibrations dissipating in the welding zone and the values of energy required for heating of the material up to melting temperature and energy required for the melting of certain amount of the material.

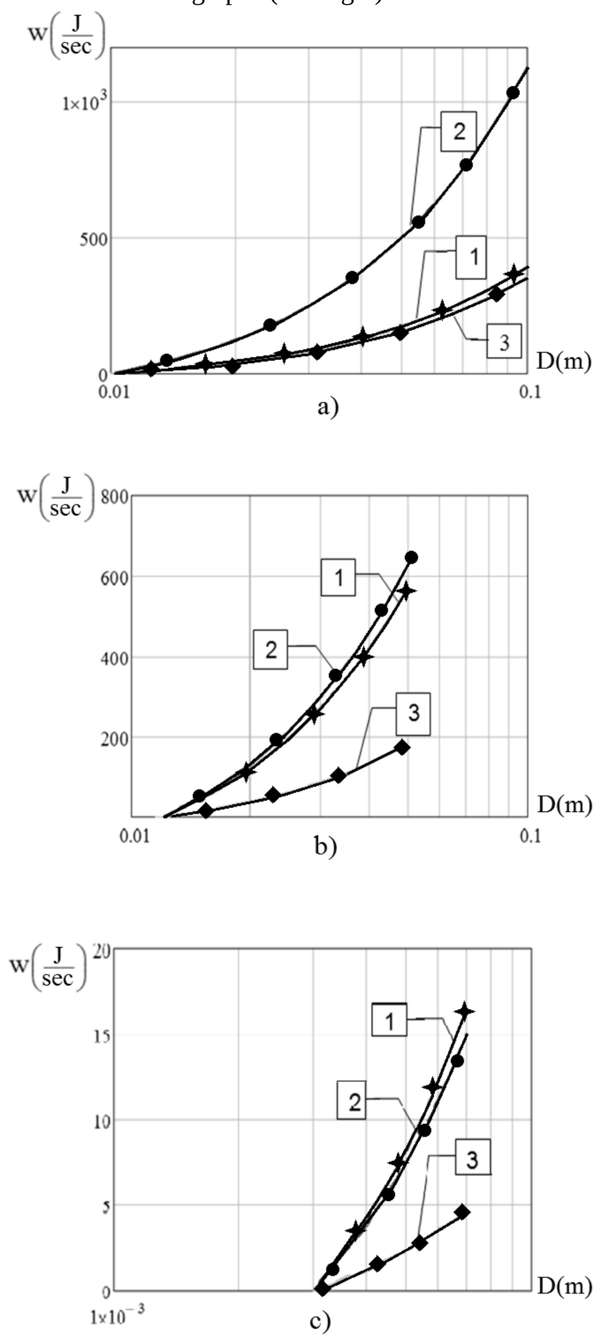
$$t = \frac{\rho_1 \cdot V_1 \cdot C \cdot dT + \lambda \cdot \rho_1 \cdot V_2}{2\pi^2 \cdot f^2 \cdot A_0^2 \cdot S \cdot \rho_0 \cdot c_0 \left(-\eta_2 \right) \left(- e^{-4\alpha x} + \eta_2 \cdot e^{-4\alpha x} - \eta_2 \cdot e^{-8\alpha x} \right)}.$$

The equation demonstrates basic expression patterns showing the dependence of ultrasonic welding time on other parameters (amplitude and frequency of the ultrasonic vibrations, the geometrical dimensions, such as the area and the thickness of formed weld, thermodynamic and acoustic properties of the materials, the density, sound velocity considering reflection and absorption of the ultrasonic energy, etc.)

Fig.4 shows the dependence of the rate of dissipation of energy of ultrasonic influence on the diameter D and the width of the welding seam formed by the welding tool. The vibration amplitude of the working welding tool is equal to A=50 micron.

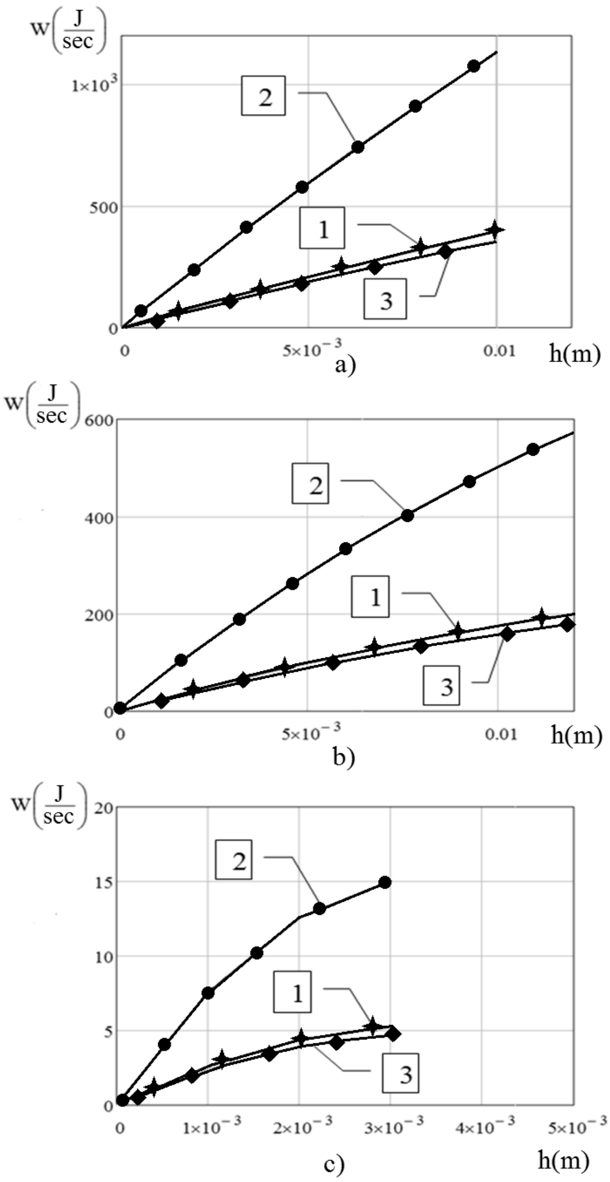
From these graphs it is evident, that the increase of the outer diameter D of ring-shaped weld the energy released in the weld zone increases exponentially.

The dependence of emitted energy from the width h of the welding tool with the outer diameter D: a) 100 mm, b) 50 mm, c) 7 mm is shown in the graphs (see Fig.5).



Outer diameter of the tools: a) 100 mm; b) 50 mm; c) 7 mm;
1 – PVC, 2 – PE, 3 – PET
Fig. 4. Dependence of energy release rate in different materials from the outer diameter of the welding tool

According to the graphs shown in Fig.5 the increase of the joint width *h* provides introducing of more energy in polymeric materials. The obtained results of ultrasonic energy corresponding to the width of ring-shaped tools are given in Tab. I.



Outer diameter of the tools: a) 100 mm; b) 50 mm; c) 7 mm;
1 – PVC, 2 – PE, 3 – PET

Fig. 5. Dependence of the rate of energy release in a variety of materials on the width of the weld (welding tool)

TABLE I
THE ACOUSTIC ENERGY DISSIPATED IN THE WELD ZONE WITH VARYING DIAMETER AND WIDTH

Power of the ultrasonic devices, VA	*S*, mm^2	*D*, mm	*W ac.theory*, J/sec		
			PVC	PE	PET
400	38	7	17	15	5
1000	1390	50	200	575	180
3000	2826	100	400	1140	360

It is evident, that at the decrease of the area of acoustic contact *S* smaller amount of ultrasonic energy is introduced in welded materials.

In Fig.6 the graphic ratio of the acoustic energy and the types of the materials and the square of ring-shaped seam is shown. The value of the releasing energy depends on the area of the welding tool.

We define the efficiency of the apparatus by the ratio of the acoustic energy released in the welding area to the power consumption.

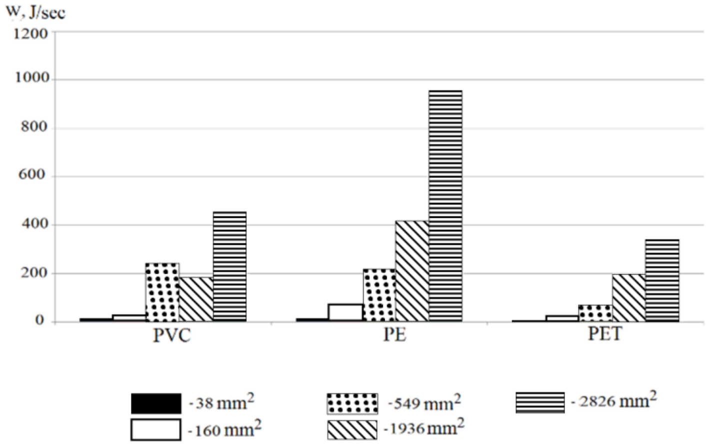


Fig. 6. Dependence of the energy emitted on the area of the welding tool.

Knowing the power consumption of the device the efficiency for three types of the devices can be calculated according to the equation:

$$\eta = \frac{W_{ac.eksp}}{P_{cons}},$$

where $W_{ac.eksp}$ is the experimental acoustic power, P_{cons} is the power consumption of the device.

TABLE II
VALUES OF ACOUSTIC ENERGY AND POWER CONSUMPTION AND THEIR EFFICIENCY

Power of the devices, VA	Power consumption of the device *Pcons*, Wt	Experimental acoustic power *Wac.eksp*, Wt			Efficiency		
		PVC	PE	PET	PVC	PE	PET
400	215	15	12,5	4	0.07	0.06	0.02
1000	630	183	415	198	0.29	0.66	0.31
3000	1250	442	950	327	0.36	0.76	0.27

According to obtained efficiency of the ultrasonic equipment it can be concluded, that the power consumption of the device is much higher than costs of energy spent on the dispersion in the zone of welded ring-shaped seam.

IV. DISCUSSION OF RESULTS

Tab. III presents (recommendations on using of devices for the formation of ring-shaped seams of various configurations) ranges of possible geometric variables of the tool and released acoustic energy, which should correspond to the power consumption of the ultrasonic devices.

TABLE III

RECOMMENDATIONS ON THE APPLICATION APPARATUSES FOR THE FORMATION OF RING SHAPE JOINTS OF VARIOUS CONFIGURATIONS

Power of ultrasonic devices, VA	*h*, mm	*D*, mm	*S*, mm^2	Value of the acoustic energy *Wac.teor*, J/sec
400	2...3	5...7	19...38	5...27
630	3...5	15...25	113...314	46...130
1000	5...7	25...50	314...945	130...370
1000	5...12	25...50	314...1431	130...590
3000	5...12	50...100	706...3316	130...1330

At the solution of two last tasks for the realization of various welding products and materials it is developed and designed welding devices (see Fig.7) for press welding of different shapes of the joints such as rivet-type joints, linear form seams, or ring-shaped seams of complex closed loop.

Fig. 7. Specialized welding apparatuses for the ultrasonic welding

V. CONCLUSION

1) It was carried out the theoretical analysis of the ultrasonic welding of thermoplastic polymeric materials; it was determined interrelation of parameters of welding materials and formed ring-shape welding joint, such as the diameter and width of the welding seam with energy released in the welding zone.

2) It was defined theoretical dependence of energy released in the area of the ultrasonic welding on the amplitude, which shows the most effective value of the amplitude of 50 microns, from diameter and width of ring-shaped weld.

3) It was carried out experimental studying of the influence of the tool square (the tool diameter and the width) on the energy releasing in the welding zone. The values of acoustic energy for various devices at the formation of ring-shaped welds of different areas were determined.

4) As a result of experimental studies it was evaluated the efficiency of ultrasonic devices with the power of 400, 1000 and 3000 VA. The recommendations on choice of ultrasonic devices of different power 400, 630, 1000, 3000 VA for the formation of ring-shaped welds of the diameters from 5...100 mm and the width of weld from 2...12 mm were proposed.

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