Theoretical Investigations of Continuous Ultrasonic Seam Welding of Thermoplastic Polymers and Fabrics

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Abstract – In the article results of theoretical investigations of formation of continuous joint in contact area of flat surface of the radiator with rotating surface of the pressure roller. On the base of analysis of distribution, reflection and absorption of ultrasonic vibrations in connected materials in the contact zone recommendation on the choice of pressure roller parameters and optimal amplitude of ultrasonic vibrations and broach speed for materials different in properties and thickness were worked out.

Index Terms – Polymer, ultrasonic welding, continuous weld seam, broach speed of materials.

I. INTRODUCTION

CONTINUOUS ULTRASONIC SEAM welding is the most perspective method of obtaining of qualitative reliable continuous joint of thermoplastic polymers and fabrics. It is widely used for formation of continuous weld seams for packaging of solid and liquid food in the polymer thermoplastic films.

II. PROBLEM DEFINITION

At present in practice continuous ultrasonic welding is realized in following ways [1]-[5]:
1. Travelling of the ultrasonic vibrating system with welding instrument of sliding type along the surface of joined materials on the fixed bearing.
2. Travelling of the ultrasonic vibrating system with welding ring-shaped instrument rotating about its axis on the surface of joined materials on the fixed bearing.

The main disadvantages of applied methods of continuous ultrasonic welding are necessity of use of work bearing tables with large area, application of complex mechanisms for travelling of welding instrument. During the use of the ultrasonic vibrating systems of rotating type the absence of concentrators (amplifier of mechanical vibrations) does not let provide vibration amplitudes necessary for high quality welding. Moreover need to transfer energy on the rotating system causes the application of special current collectors, that makes the construction more complicated and reduces the reliability at energy transfer.

In this connection in recent years ultrasonic devices with rotating mounting in the form of roller are widely used. Configuration of weld seam, its width and form depend on width and form of surface of pressure roller. The quality of formed joint is determined not only by parameters of ultrasonic influence (amplitude, frequency, time), but also by parameters of pressure roller, speed of its rotation and contact area at the changes of material properties and thickness [6]-[9].

It is evident, that for designing of universal ultrasonic equipment based on the realization of this welding method it is necessary to provide the possibility of its operative reconstruction, setting and stabilization of necessary vibration amplitude at the changes of broach speed of materials different in properties and thickness at any any possible changes of welding instrument and pressure roller configurations, its width and form of the surface (hatching).

For creation of such universal equipment there is a need in information on parameters of necessary ultrasonic influence and its tuning range [10]-[12]. As a result of this we create a model of formation of continuous weld seam in thermoplastic polymers using ultrasonic devices with rotating anvil in the form of roller.

III. THEORY

In Fig.1 the process of formation of continuous joint in thermoplastic polymer materials by ultrasonic welding using as an anvil rotating roller is presented.

Welded materials 2 and 3 having acoustic impedance \( Z_2 = \rho_2 c_2 \) and thickness \( X \) each are limited from the one side with working welding instrument 1 of the ultrasonic vibrating system with acoustic impedance \( Z_1 = \rho_1 c_1 \) from the other side with roller 4 with acoustic impedance \( Z_4 = \rho_4 c_4 \), to which welded materials are pressed by the working welding instrument of the ultrasonic vibrating system under the pressure \( P \) and air with acoustic impedance \( Z_0 = \rho_0 c_0 \).

![Fig. 1. Process of continuous ultrasonic seam welding of thermoplastics: 1 – welding instruments, 2,3 – welded materials, 4 – roller, 5,6,7,8 – boundary of media, 9 – zone of welding](image)

Zone 9 will correspond to the zone of absorption of ultrasonic vibrations, heat generation and formation of joint weld in the volume of welded materials limited with surface area \( S \) and...
thickness of materials 2X. Ultrasonic vibrations generated and amplified by the vibrating system are introduced in the boundary of media of the welding instrument of the ultrasonic vibrating system and welded materials 5. Intensity of ultrasonic vibrations generated at the radiating surface of the ultrasonic vibrating system can be presented as

\[ I_0 = 2\sqrt{2}\pi f A e \]  

(1)

Taking into account that during the ultrasonic welding complete acoustic contact of welding ultrasonic vibrating system and welded materials is provided, in boundary 5 reflection of ultrasonic wave takes place, and a part of ultrasonic vibrations goes through the boundary to welded material 2. Reflection coefficient \( \eta_1 \) and transmission coefficient of wave \( d \) in the boundary of media can be defined.

\[ \eta_1 = \left( \frac{\rho_0 c_0 - \rho_1 c_1}{\rho_0 c_0 + \rho_1 c_1} \right)^2 \]  

(2)

\[ d = 1 - \eta_1 \]  

(3)

Then in the thermoplastic material 2 with acoustic impedance \( \rho_1 c_1 \) wave with the intensity will be entered

\[ I_2 = I_1 e^{-2\alpha x} \]  

(4)

Energy of dissipation, i.e. energy being absorbed by thermoplastic material 2 with acoustic impedance \( \rho_1 c_1 \), the passing of ultrasonic vibrations can be calculated following way:

\[ W = (I_1 - I_1 e^{-2\alpha x}) S \]  

(5)

where \( \alpha \) is a damping coefficient on amplitude, \( I_1 e^{-2\alpha x} \) is an intensity of ultrasonic vibrations in boundary 6, where \( 2\alpha x \) is a way passed by wave. As for the formation of joint weld, providing of passing through the boundary of welded materials as much as possible energy of ultrasonic vibrations it is necessary to guarantee complete acoustic contact, boundary 6 is represented acoustically transparent and transmission coefficient \( d \) will equal 1. So the intensity of ultrasonic vibrations absorbed in material 3 can be calculated as

\[ I_3 = I_1 e^{-2\alpha x} - I_2 e^{2\alpha x} \]  

(6)

Energy of wave reflected from boundary welded material – air and roller 4 should also be taken into account for definition of energy being absorbed by the material 3. It is possible to note reflection from the boundary with air 8. Then we find reflection coefficients \( \eta_2, \eta_3 \) and calculate intensity of reflected from boundary 7 and 8 waves.

\[ \eta_2 = \left( \frac{\rho_2 c_2 - \rho_1 c_1}{\rho_2 c_2 + \rho_1 c_1} \right)^2 \]  

(7)

\[ \eta_3 = \left( \frac{\rho_3 c_3 - \rho_2 c_2}{\rho_3 c_3 + \rho_2 c_2} \right)^2 \]  

(8)

\[ I_{21} = \eta_2 I_1 e^{-4\alpha x} \]  

(9)

\[ I_{31} = \eta_3 I_1 e^{-4\alpha x} \]  

(10)

Subject to energy of reflected waves it is possible to calculate intensity of reflected energy being absorbed by welded materials in the weld zone.

\[ I_{32} = \eta_3 I_1 e^{-4\alpha x} - \eta_3 I_1 e^{-8\alpha x} \]  

(11)

In case intensity of ultrasonic vibrations and energy absorbed in the case material 3 taking into consideration of energy of reflected waves and contact area with roller \( s \) are calculated in a following way.

\[ I_2 = I_1 e^{-2\alpha x} - I_1 e^{-4\alpha x} + \eta_1 I_1 e^{-6\alpha x} - \eta_1 I_1 e^{-8\alpha x}, \]

(13)

\[ W_2 = I_1 e^{-2\alpha x} S - \eta_2 I_1 e^{-4\alpha x} S + \eta_1 I_1 e^{-6\alpha x} S - \eta_1 I_1 e^{-8\alpha x} S + \eta_2 I_1 e^{-4\alpha x} (S - s) - \eta_1 I_1 e^{-6\alpha x} (S - s) \]  

(14)

On the grounds of (5), (13), (14) it is possible to define total energy, which is absorbed by medium 9 of thermoplastic materials during the ultrasonic welding.

\[ W = I_1 (1 - e^{-2\alpha x} S - e^{-4\alpha x} S + \eta_2 e^{-4\alpha x} S - \eta_1 e^{-6\alpha x} (S - s) - \eta_1 e^{-8\alpha x} (S - s)) \]  

(15)

Entering value of intensity of ultrasonic vibrations in the media taking into account different acoustic impedances, reflection coefficients, the expression (4) is substituted in (15), after that speed of energy dissipation of ultrasonic vibrations or instantaneous speed of heat generation in welded materials will be obtained:

\[ W = 2\pi J^2 \rho_0 c_0 (1 - \eta_1) (S - e^{-2\alpha x} S - e^{-4\alpha x} S + \eta_2 e^{-4\alpha x} S - \eta_1 e^{-6\alpha x} (S - s) - \eta_1 e^{-8\alpha x} (S - s)) \]  

(16)

Obtained expression lets determine dependence of time of ultrasonic influence for the formation of weld seam on energy of ultrasonic vibrations dissipated in the weld zone and the value of energy, which is necessary to heat the material to melting temperature, and energy, which is required for melting of defined volume of the material taking into account the expression (16):

\[ \rho_1 V_1 \int_{T_{nk}} T_{nk} C_dT + \lambda \rho_2 V_2 + Q_3 \]  

\[ t = \frac{T_{nk} W}{W} \]  

(17)

The expression (17) represents the main laws showing the dependence of time of the ultrasonic welding on other parameters (amplitude and frequency of ultrasonic vibrations, area and thickness of formed weld seam, acoustic and thermodynamic properties of the materials, density, speed of sound, etc.). The value \( Q_3 \) characterizes some loss of heat in the weld zone.

One of the main features of continuous seam welding is broach speed of welded materials, we calculate it on the base of the expression:

\[ V_{np} = \frac{l}{t} \]  

(18)

where \( l \) is a length of instantaneous weld zone, \( t \) is a time of welding.

Starting from expressions (17) and (18) we obtain the expression for broach speed:

\[ V_{np} = \frac{\int_{T_{nk}} W \cdot l}{\rho_1 V_1 \int_{T_{nk}} C_dT + \lambda \rho_2 V_2 + Q_3} \]  

(19)

In Fig. 2 dependence of broach speed on vibration amplitude of working welding instrument for polymeric thermoplastic materials different in properties is demonstrated.
Obtained dependences were defined for polyethylene terephthalate, polystyrene, polyethylene taking into account their acoustic properties.

All calculations were carried out for sheet materials with thickness of 0.1 mm and area of welding instrument of 25 mm². From obtained dependences it result that at the growth of vibration amplitude broach speed should be increased. It can be explained that at the growth of vibration amplitude the speed of energy dissipation in the material considerably increases.

In Tab. I values of energy required for welding of polyethylene film with thickness of 0.1 mm and dissipation energy in the weld zone in sec depending on the area of fomenting of ultrasonic vibrations (instantaneous area of welding) are shown.

<table>
<thead>
<tr>
<th>Instantaneous area of welding (mm²)</th>
<th>Required energy (J)</th>
<th>Dissipation energy in the weld zone in sec (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>75</td>
<td>2.49</td>
<td>11.71</td>
</tr>
<tr>
<td>60</td>
<td>1.99</td>
<td>9.37</td>
</tr>
<tr>
<td>45</td>
<td>1.49</td>
<td>7.03</td>
</tr>
<tr>
<td>30</td>
<td>0.997</td>
<td>4.68</td>
</tr>
<tr>
<td>15</td>
<td>0.498</td>
<td>2.34</td>
</tr>
</tbody>
</table>

In Fig. 3 dependences of formation speed of joint weld on the contact area of the material with the roller are demonstrated.

Obtained dependences show, that width of pressure roller influences on the release of ultrasonic energy in the weld zone and on the productivity of the process. It is stated, that maximum release of ultrasonic energy in welded materials is realized due to reflection from the boundary 8 of welded materials and air. It is achieved at minimum contact with the roller and lets at the reduce of contact area with pressure roller increase broach speed of welded materials and provide improved productivity of the process.

**IV. CONCLUSION**

As a result of theoretical analysis of ultrasonic welding with the application of rotating anvil according to proposed model it was ascertained limits of reconstruction of the ultrasonic equipment on power, vibration amplitude, which are necessary for providing of qualitative joining of different materials, and limits of adjustment of broach speed depending on materials different in properties and thickness, for pressure roller varying in the area and form of the surface.

**REFERENCES**


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