

The Influence of the Surface Friction on the Process of Continuous Ultrasonic Welding of Thin Polymer Films

Andrew V. Lehr, *Student Member, IEEE*, Vladimir N. Khmelev, *Senior Member, IEEE*, Viktor A. Nesterov, *Student Member, IEEE*, Aleksey N. Slivin
Biysk Technological Institute (branch) Altai State Technical University after I.I. Polzunov, Biysk,
Russia

Abstract – The article is devoted to theoretical investigations of the continuous ultrasonic welding of thin polymer films. Theoretical studies of the process of energy release of ultrasonic vibrations in the welding zone let ascertain, that friction energy during the continuous welding of the films with small thickness (less than 0.5 mm) influences on the productivity of the continuous welding.

Index terms – Welding, ultrasound, thermoplastic, film, friction.

I. INTRODUCTION

At present to obtain continuous welding seam of polymer materials three technological methods are applied in industry. They are gluing, thermal and ultrasonic gluing. However for gluing of polymers plenty of special glues and thorough cleaning of joined surfaces from fats, oils and other polutions are required. Thus gluing and thermal welding do not provide necessary quality of continuous welding seam of polymer materials.

The ultrasonic welding is the most perspective way of obtaining of continuous welding seam.

According to the researches [1, 2] the main parameters of the welding process are interrelated, the quality of formed continuous welding seam depends on the value of ultrasonic energy liberated in the welding zone. In turn the energy liberated in the welding zone is determined by the frequency, the amplitude of ultrasonic vibrations, the contact area and speed of broach of welded materials. This welding is mostly used for joining of packing materials (thin list polymers – films).

Unfortunately, the processes taking place during the formation of continuous welding seam in thin films are not studied, there is no information on the mechanism of liberation of necessary and sufficient energy.

This does not allow to set optimal modes of influence during the use of existing ultrasonic welding apparatuses and develop the new ones.

II. PROBLEM STATEMENT

Nowadays there are no models of the process of ultrasonic welding, which are able to take into consideration all basic processes occurring in the welding zone. These processes are so transient and they quickly alternate, that it is very difficult to take them into account. The most difficult for mathematical formulation is the welding process of thin films. There are some separated descriptions of the phenomena taking place during such welding [3].

The papers [2,3] propose the design procedure considering heating and plasticization of polymer during the welding due to the dissipation of entered and reflected ultrasonic energy. However in practice proposed by the authors the design procedure of the productivity of continuous welding concerning to thin films do not give reliable results. The design capacity was lower than real.

It is evident, that the reason of the disagreement between theoretical and practical results are in the following, there are some factors, which were not taken into account earlier.

It is caused the studies of the continuous welding of thin films in detail in order to find out the reasons influencing on the productivity of the process and the ways of its increase.

III. THEORY

Figure 1 shows the process of the propagation of ultrasonic vibrations at the formation of continuous welding seam in thermoplastic polymer materials by the ultrasonic welding using revolving roller.

The welded materials 2 and 3 characterized by the acoustic impedance $Z_1 = \rho_1 c_1$ and having X thickness each are limited by the working welding tool 1 (Figure1) of the ultrasonic vibrating system with the acoustic impedance from the one side

$$Z_0 = \rho_0 c_0,$$

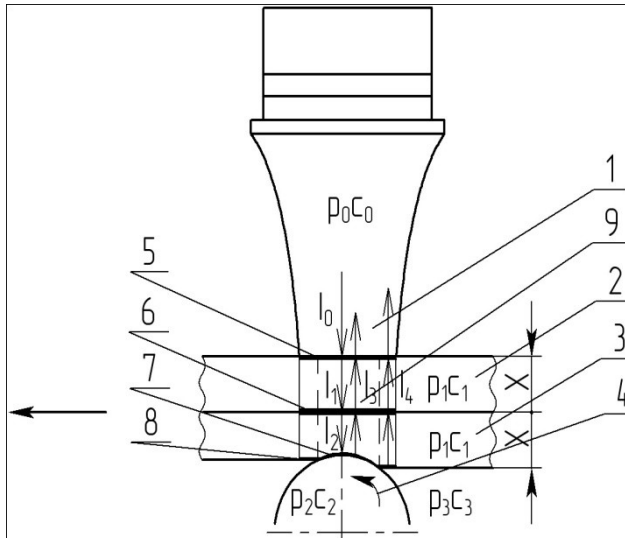
from the other side by the roller 4 with the acoustic impedance

$$Z_2 = \rho_2 c_2.$$

Welded materials are pressed to the roller by fixed gap of the the welding tool – the supporting roller and air with the acoustic impedance

$$Z_3 = \rho_3 c_3,$$

where ρ is the density of the medium, c is the speed of sound in this medium.



1 – welding tool, 2,3 – welded materials, 4 – the roller, 5,6,7,8 – the interface of the media, 6 – the friction zone, 9 – the welding zone

Fig. 1. – The diagram of the continuous seam ultrasonic welding of the thermoplastics

The zone of the absorption of ultrasonic vibrations, heat release and formation of welding joining will correspond the area 9 in the volume of welded materials restricted by the area of the surface S and the thickness of the materials $2X$. Ultrasonic vibrations generated and amplified by the vibrating system are entered into the interface of the media of welding tool of the ultrasonic vibrating system and welded materials 5. The ultrasonic vibrations with the specified intensity are generated on the radiating surface of the ultrasonic vibrating system.

One of the main characteristics determining of the efficiency of continuous seam welding is the productivity of the process, i.e. speed of broach of welded materials and the formation of seam. To calculata the speed of broach the expression obtained in the paper [3] is used:

$$V_{br} = \frac{W \cdot l}{\rho_1 V_1 \int_{T_s}^{T_m} C dT + \lambda \rho_1 V_2 + Q_3}, \quad (1)$$

where ρ_1 is the density of welded materials, V_1 is the volume of heated material, T_m is the melting temperature of the polymer, T_s is the initial temperature, C is the specific heat of welded materials, λ is the specific melting heat of welded materials, V_2 is the volume of melted material, Q_3 is some loss in the welding zone, speed of heat release in welded materials:

$$W = 2\pi^2 f^2 A_0^2 \rho_0 c_0 (1 - \eta_1) (S - e^{-2\alpha x} S - e^{-4\alpha x} S + \eta_2 e^{-4\alpha x} S - \eta_2 e^{-8\alpha x} S + \eta_3 e^{-4\alpha x} (S - s) - \eta_3 e^{-8\alpha x} (S - s)), \quad (2)$$

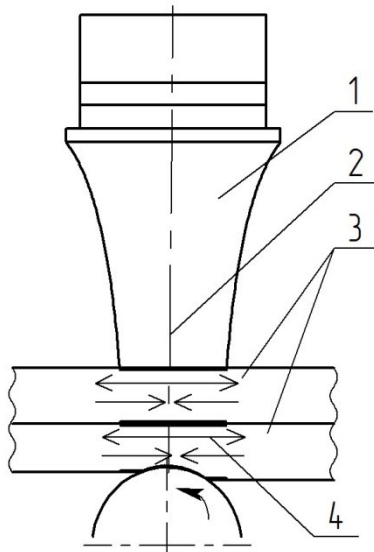
f is the frequency of vibrations, A is the amplitude, l is the length of instantaneous welding zone, η is the reflection coefficient depending on the interface is calculated according the formula:

$$\eta_1 = \left(\frac{\rho_0 c_0 - \rho_1 c_1}{\rho_0 c_0 + \rho_1 c_1} \right)^2. \quad (3)$$

As investigations showed [4], during the welding of materials, which thickness is less than 0.5 mm, in the zone of ultrasound channel and near it there were transverse (relative to the axis of introduction of ultrasonic vibrations) displacements of welded materials (zone 6 Fig. 1). These displacements can explain sharp increase of productivity of welding of thin polymer films in practice, as it leads to rise of the energy of surface friction between welded materials in comparison with the contribution of friction energy during the welding of materials with larger thickness (> 0.5 mm).

The reason of increase of surface friction in the zone of channel is transverse displacements caused by the appearance of the effect of “hammer and anvil” At the same time the polymer under the action of displacements of the face of the tool and static pressure is deformed in longitudinal direction in all its thickness and shifted in the peripheral zones of the axis of the channel [4], as shown in Fig. 2. The friction between welded materials hypothetically appears because of differences in the phase of transverse displacements of welded materials relative

to each other, which equals to $\frac{\pi}{2}$.



1 – the tool, 2 – the axis of acoustic channel, 3 – welded materials, 4 – transverse displacements

Fig. 2 – The transverse displacements of welded materials in the peripheral zone relative to the axis of the channel

The energy released due to the surface friction of welded materials at the relative displacement of upper material to the lower one according to the energy conservation law can be calculated as a work of friction forces of one deformation cycle:

$$E_{tr} = F_{tr} \cdot s, \quad (4)$$

where F_{tr} is the friction force, and s is the displacement of the upper material relative to the lower one. The friction force can be calculated applying the law of Amontons-Coulomb:

$$F_{tr} = \mu F, \quad (5)$$

where μ is the coefficient of friction, and F is the force of normal reaction at the support:

$$F = pS, \quad (6)$$

where p is the maximum acoustic pressure in the substance of welded materials

$$p = 2\pi f \rho c A \quad (7)$$

, and S is the area of friction (is accepted equal to the area of the welding zone Fig. 2).

Hence, substituting (5), (6) and (7) into (4) we get:

$$E_{tr} = \mu p S s. \quad (8)$$

For one deformation cycle taking into account the transformation of longitudinal wave into transverse the mixture of displacement of welded materials occurs [4]:

$$s = 4A, \quad (9)$$

where A is the amplitude of entered vibrations. Substituting (7) and (9) into (8) taking into

consideration the frequencies of vibrations we get the expression for the rate of energy release of the surface friction:

$$W_{tr} = 8\mu\pi\rho c S A^2 f^2. \quad (10)$$

Summing the rate of energy release of the surface friction W_{tr} with dissipation rate W we get broach rate of welded materials (1) subject to friction energy:

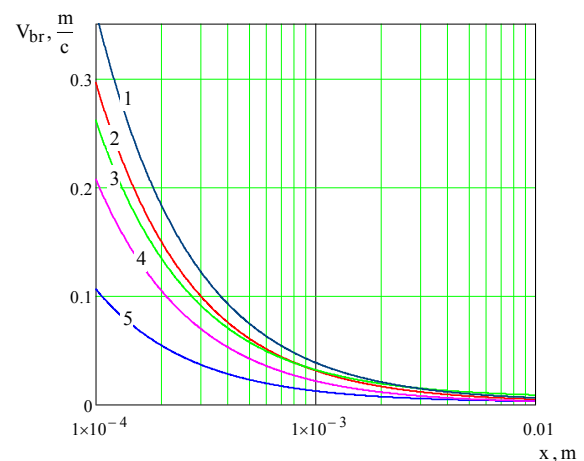
$$V_{br} = \frac{(W + k \cdot W_{tr}) \cdot l}{T_m \rho_1 V_1 \int_{T_s} C dT + \lambda \rho_1 V_2 + Q_3}, \quad (11)$$

where k is the proportionality coefficient (<1) compensating some unaccounted factors such as the absence of constant contact in the zone of surface friction and changes of the acoustic pressure in the welding zone due to stepwise change of the properties of welded materials.

Based on the expression (11) the dependences of broach rate of welded materials on such influencing factors as the thickness of welded materials, the amplitude and the frequency of entered vibrations were studied.

Fig. 3 shows the graphs of dependences of rated speed of broach of welded materials different in thickness

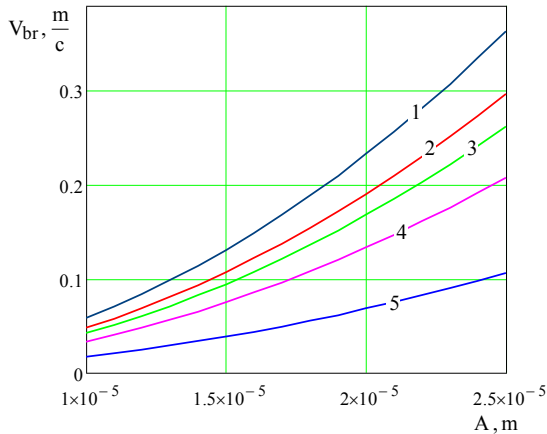
As it follows from the graphs (Fig. 3) with the decrease of the thickness of welded materials rated speed of welding essentially increases. It can be explained by the fact, that with the decrease of the thickness the dissipation energy W and energy, which is necessary for welding, decrease proportionally, and the friction energy W_{tr} remains unchanged, as it does not depend on the thickness.



1 – polystyrene, 2 – pvc, 3 – polyethylene, 4 – polyethylene terephthalate, 5 – polypropylene

Fig. 3 – The graph of the dependences of the rated speed of broach of different welded materials on their thickness

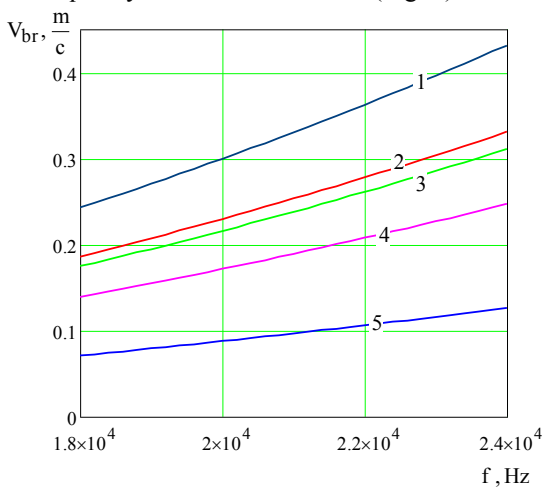
Fig. 4 shows the graphs of the dependences of rated speed of broach of different welded materials on the amplitude of entered vibrations.



1 – polystyrene, 2 – pvc, 3 – polyethylene, 4 – polyethylene terephthalate, 5 – polypropylene

Fig. 4 – the graph of dependences of rated speed of broach of different welded materials on the amplitude of entered vibrations

Based on the dependences presented in Fig.4 taking into account the expressions (10) and (11) for the rate of energy release of the surface friction and the rate of broach respectively it is possible to estimate increased contribution of the amplitude and the frequency of entered vibrations (Fig. 5).



1 – polystyrene, 2 – pvc, 3 – polyethylene, 4 – polyethylene terephthalate, 5 – polypropylene

Fig. 5 – The graph of dependences of rated speed of broach of different welded materials on the frequency of entered vibrations

Thus the estimation of the influence of friction energy during the continuous welding of thin films showed, that the phenomenon of external friction was the main influencing factor determining the possibility of increase of welding productivity. For comparison table 1 presents the results of theoretical

calculations of rates of energy liberation providing welding.

TABLE I
RATES OF FRICTION AND DISSIPATION ENERGY LIBERATION RELATIVE TO TOTAL RATE OF ENERGY LIBERATION IN THE WELDING ZONE OF FILMS 0.1 MM THICK

Material	Rate of friction energy liberation (J/sec)	Rate of dissipation energy liberation (J/sec)	Total rate of energy liberation (J/sec)
Pvc	61.201	0.357	61.558
Polypropylene	41.054	0.706	41.76
Polyethylene	42.385	0.984	43.369
Polyethylene terephthalate	81.253	0.326	81.579
Polystyrene	49.037	0.344	49.381

From the data presented in Table 1 it follows, that the friction energy during the continuous welding of the films with small thickness (less than 0.5 mm) influences on the rate of the welding process. Using obtained data it can be assumed, that maximizing the parameters (the amplitude and the vibration frequency) which positively influence on the friction, it is possible to increase the productivity of continuous welding of thin films.

At present the development of the device for seam ultrasonic welding is aimed at the production of the technological equipment with working frequency of more than 22 kHz and the vibration amplitude of up to 80-100 micron.

III. CONCLUSION

As a result of carried out researches the process of continuous welding of thin films was studied:

1. It was found out, that the determining factor influencing on the productivity of the continuous welding of thin films is the surface friction between welded materials.
2. The theoretical dependences of rated capacity of the continuous welding on the parameters, entered ultrasonic vibrations and the properties of welded materials were obtained.
3. The analysis of obtained data let recommend to increase the productivity of welding by the intensification of the processes of the surface friction in particular by the creation of the technological equipment with the frequency of more than 22 kHz and the vibration amplitude of up to 80-100 micromicron.
4. To increase the productivity of welding it can be proposed the intensification of the processes of the surface friction due to the application of the supporting roller with cutters on the working surface, it can decrease the amplitude of

transverse displacements of the lower material and increase the amplitude of the surface friction.

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Viktor A. Nesterov. In this time he is student of Biysk Technological Institute. IEEE Student Member.



Alexey N. Slivin Ph.D was born in Biysk, Russia, 1976 He received degree on information measuring engineering and technologies from Altay State Technical University, key specialist of electronics. His main research interest are development of high-power electronic generators for ultrasonic technological welding.



Andrew V. Lehr was born in Barnaul, Russia, 1988 He get a higher education on information measuring engineering and technologies from Altay State Technical University. His main research interest is continuous ultrasonic seam welding of thermoplastic polymers and fabrics.



Vladimir N. Khmelev (SM'04) - pro-rector at Biysk technological institute, professor, Full Doctor of Science (ultrasound). Honored inventor of Russia. Laureate of Russian Government premium for achievements in science and engineering. Area of scientific interests is application of ultrasound for an intensification of technological processes. IEEE member since 2000, IEEE Senior Member since 2004. His biography published in 7th issue of book "Who is who in scientific and engineering"