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MODELING OF THERMAL PROCESSES IN LASER WELDING OF POLYMERS

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ABSTRACT

In the work, a mathematical description of thermal processes in laser welding with the use of the classical theory of thermal conductivity was performed. The thermal cycle under the action of radiation on the surface was analyzed using the models of overall heat balance, distributed surface, point, circular and linear heat sources. The modeling of welding process consisted in solving the problem of forming thermal fields in viscoelastic polymer materials at a moving inner heat source. It was assumed that the upper part is transparent to laser radiation and the lower one has a set coefficient of light beam absorption, and their thermophysical characteristics depend on temperature. The equations of thermal conductivity and defining equations were formulated, supplemented by the boundary conditions of convective heat transfer and the initial temperature distribution. For the numerical implementation of certain equations the finite element method was used, which is based on an alternative formulation of the problem. The results of mathematical modeling showed the peculiarities of the formation of thermal fields in the transmission laser welding of polymer films at different parameters of welding mode.

KEY WORDS: laser welding, polymer films, mathematical modeling, thermal processes, temperature fields, isotherms

INTRODUCTION

The general term "radiation welding" combines methods for welding plastics with heating of the joint zone due to the conversion of the electromagnetic radiation energy of visible and infrared (IR) spectrum regions into heat [1, 2]. Light radiation occupies the range of electromagnetic wave length in the range of 0.2–1.0 μm, and infrared — from 1 to 2000 μm. The laser source creates radiation of a narrow wavelength range in visible or infrared spectrum regions, depending on type of laser. Depending on type of radiation source, three methods of welding are distinguished: infrared radiation, light welding and laser welding.

Nowadays, the most common technology of laser welding of polymer materials is welding of overlapped joints using transmission (penetrating) method. The essence of this method consists in the fact that a short-wave laser radiation of the optical or near IR region passes through a part of the welded joint which is transparent for it and absorbed with the release of heat on the contact surface of parts. A variant is also possible when laser radiation is partially absorbed by both billets by heating the welding zone.

The main feature of laser transmission welding of plastics is the need to select materials with such properties that provide absorption of laser radiation on a certain surface of the welded joint. The most widespread use belongs to that transmission overlap laser welding of sheet polymer materials when radiation passes through the upper transparent sheet and is absorbed by the lower nontransparent one. As a result, heating of nontransparent material is observed and due to heat transfer, the whole welding zone is heated up. In such a way, polymer films or thin plates are usually welded [3].

Technologically, laser welding is more complex as compared to other methods. Sometimes it is quite difficult to determine the optimal parameters of the transmission laser welding process, in particular for thin films. Therefore, the mathematical modeling of thermal processes is relevant during this method of welding for theoretical substantiation of optimal parameters of the mode [4–6].

The properties of laser radiation significantly distinguish it from radiation of any other incoherent sources. Therefore, it is necessary to separately consider the problem of interaction of laser radiation with a substance [7]. Polymers have a complex molecular structure, so they interact differently with radiation of different wavelengths [8]. Most polymers in a pure form without dyes and impurities are transparent in the visible and near infrared range of the spectrum. For transmission laser welding, the most versatile is diode (semiconductor) lasers. These lasers are produced with many values of length of the visible and near infrared radiation ranges (from 0.4 to 1.45 μm). They have a relatively low cost and efficiency coefficient at the level of 60 %.

It is known [9] that when absorbing the radiation by a substance, the quanta power is converted into heat, whose distribution in the material occurs due to the thermal conductivity. In most cases, it can be assumed that light energy instantly converts into heat in the point where radiation is absorbed. Based on this assumption, the description of thermal processes for laser welding can be carried out using a classical theory of heat conductivity [10].

An analytical description of the thermal cycle under the action of radiation on the surface is possible in the analysis of the following models: overall thermal balance; distributed surface source (one-dimensional case); point thermal source; circular source; linear source.

OVERALL HEAT BALANCE

If we assume that all radiation energy is spent on melting a polymer that is then removed, then in this case

$$P(1-R) = \nu b h \rho (c\Delta\theta + L_{ie}), \tag{1}$$

where P is the power of radiation acting on the material; b is the width of a cut zone; L_{ie} is the latent melting heat; h is the depth of notches; c is the heat capacity, ρ is the density of material.

DISTRIBUTED SURFACE SOURCE (ONE-DIMENSIONAL THERMAL FLOW)

For polymers with a high absorption index (filled with a technical carbon) and for which the ratio $\delta = \alpha^{-1} << (at)^{1/2}$ is performed, where δ is the penetration depth of the beam; α is the index of absorption of radiation by medium; α is the temperature conductivity; t is the radiation time, the heat source can be considered superficial [7]. In this case, the temperature distribution in the polymer and its change in time are determined by the thermal conductivity of the medium and described by the following equation:

$$\theta(z,t) = \frac{2q(at)^{1/2}}{\lambda_T} ierfc \frac{z}{2(at)^{1/2}}, \tag{2}$$

where $q = E(1–R)$, *ierfc* is an integral of errors; λ is the coefficient of thermal conductivity.

Temperature on the surface of material

$$\theta(0,t) = \frac{2q}{\lambda_T}\left(\frac{at}{\pi}\right)^{1/2}. \tag{3}$$

This model can be used on the condition that the radius of the laser beam is much larger than the size of the surface irradiated during the time t.

POINT HEAT SOURCE

The solution of the heat conductivity equation on the condition of absence of convection and radiation losses, and in the assumption that the heat source is instantaneously acting at the point with the coordinates (x', y', z') can be provided in the form:

$$\theta(x,y,z,t) = \frac{Q(x',y'z')}{8(\pi at)^{3/2}} \times \exp\left(-\frac{(x-x')^2 + (y-y')^2 + (z-z')^2}{4at}\right), \tag{4}$$

where Q is the amount of heat released in the volume of material.

In case of symmetrical heat distribution for a thin plate $H/4\alpha t << 1$, the following ratio is fair:

$$\theta(r,t) = \frac{Q}{4\pi\lambda_T Ht}\exp\left(-\frac{r^2}{4at}\right). \tag{5}$$

For a moving source in a thin plate, the following ratio is fair:

$$\theta = \frac{P(1-R)}{2\pi\lambda_T H} K_0\left(\frac{r\nu}{2a}\right)\exp\left(-\frac{\nu x}{2a}\right), \tag{6}$$

where K_0 is the Besel function of the second type of zero order.

CIRCULAR SOURCE

For most lasers, the pulse normalized by a unit in a maximum, has approximately one and the same shape if it is considered as a function of time related to the pulse duration and can be characterized in time by the function $P(t) = E(t)/E_m$. As a spatial profile of the beam, for which temperature curves will be built, it is rational to select beams with the Gaussian distribution of power density $E(r) = = E_0 \exp(-r^2/r_0^2)$.

Accordingly, the density of the flow absorbed by the surface is described by the equation:

$$q(r) = q_0 \exp(-r^2/r_0^2). \tag{7}$$

Integrating the expression in time, it is possible to obtain a solution for an instantaneous point source with a Gaussian profile. It is possible to simplify the expression for the temperature by comparing the process of heat saturation and the time when the beam passes a distance equal to its radius in time (r_0/v). If $vr_0/a<1$, then the heat source can be considered such that slowly moves. In this case, the maximum temperature of the material is achieved in the center of the moving zone of irradiation and its value differs little from the largest one, which corresponds to a stationary heat source:

$$\theta \approx \frac{E(1-R)}{\lambda_T}\left(1 - \frac{\nu r_0}{4a}\right). \tag{8}$$

The given expression is fair, if à~10^{-1}ñì^2/ñ at the speeds lower than 1 cm/s and if the diameter of the beam on the surface of the polymer is not larger than 0.5 mm.

If the time r_0/v is longer than the time of heating the plate (sheet) H^2/a, then the temperature on the surface can significantly depend on the thickness of a product:

$$\theta \approx \frac{E(1-R)r_0^2}{2\lambda_T H}\ln\frac{2.25a}{r_0\nu}. \tag{9}$$

From the last expression it follows that the threshold power density required to achieve the set temperature in the stationary mode, linearly grows with an increase in the thickness of the sheet H and weakly (logarithmically) depends on the speed of the source movement.

With an increase in the speed of the source movement, the thermal effect of radiation action decreases and the maximum temperature shifts to the periphery of a moving light spot in the opposite direction to the speed vector. In this case, during transition to high speeds, when $vr_0/a >> 1$, the value of the maximum temperature on the axis of the source movement is determined by the formula

$$\theta \approx \left(\frac{8}{\pi}\right)^{1/2} \frac{E(1-R)}{\lambda_T}\left(\frac{ar_0}{\nu}\right)^{1/2}. \tag{10}$$

The maximum temperature, to which the polymer is heated, corresponds to a surface temperature of semispace under the action of a pulsed heat source with the duration $2r_0/v$, which corresponds to the time passage of a moving source of its diameter. Therefore, for the polymers à<10^{-2}ñì^2/ñ, a condition of a fast moving source $vr_0/a >> 1$ is provided.

Modeling of thermal processes in transmission laser welding of sheet polymer materials consisted in solving the problem of the formation of thermal fields in viscoelastic polymer materials at a stationary and a moving inner source of heat energy. It is accepted that the upper part is transparent for laser radiation, the lower part has a set absorption coefficient of a light beam, and their thermophysical characteristics depend on temperature. For some polymer materials, this dependence may be established experimentally. The thermal conductivity equation and defining equations are supplemented by the boundary conditions of a convective heat transfer and the initial temperature distribution.

FORMULATION OF THE PROBLEM

Polymer films are modeled as plates in the form of rectangular parallelepipeds of different thickness located one on one. The axis of the laser beam is directed perpendicularly to the surface of the plates and a circular heat source is located in the plane of their contact.

The beginning of the Cartesian coordinate system is located on crossing the axis of the laser beam with the upper surface of the plates. The axis z is directed along the axis of the beam, the axis x is in the plane of the plates butt and is aimed in the direction, the opposite to the direction of moving the laser beam, and the axis y is perpendicular to the butt. In the chosen system of coordinates moving together with the beam, the plates are moved at the speed of welding v, and the beam is immovable.

In the mathematical model, the processes of heat transfer during welding are described by a quasi-stationary equation of heat conductivity, and heat exchange with the environment and between the subregions of the polymer material in different phases — by nonlinear boundary conditions of thermal balance. The coefficient of temperature conductivity is a constant having values in different subregions of the calculated region, which are equal to some of its average values for a particular phase of the metal in the appropriate subregion.

To simplify the problem, let us average the three-dimensional quasi-stationary heat equation along the coordinate y, as a result of which we obtain:

$$c_{ei}\nu\frac{\partial\theta}{\partial x} = \lambda_i\left(\frac{\partial^2\theta}{\partial x^2}+\frac{\partial^2\theta}{\partial z^2}\right) - \frac{\lambda_i}{l_Q^2}(\theta-\theta_a), \tag{11}$$

where effective heat capacity is calculated by the formula:

$$c_{ei} = \left\{\begin{array}{ll} c_1\rho_1 & \theta<\theta_e \\ c_2\rho_2\left(1+\dfrac{k}{c_2}\dfrac{\partial f_1(\theta)}{\partial\theta}\right), & \theta_e\le\theta\le\theta_{l0} \\ c_3\rho_3 & \theta_{l0}<\theta \end{array}\right\}. \tag{12}$$

In this equation, the index $i = 1, 2, 3$ determines the parameters of the solid, liquid-solid and liquid phases, respectively; C_i, ρ_i, λ_i is the heat capacity, density and thermal conductivity of the i-phase, respectively; κ is the specific heat of melting; θ_{l0}, θ_e are the temperatures of the beginning and end of solidification; $l_\Theta = 2\sqrt{a_i\tau}$ is the length of distribution of the thermal wave over the time $\tau = 2r_F/v$, r_F is the radius of the beam in the focal plane; a_i is the temperature conductivity of the i-th medium; θ_a is the characteristic temperature of the plate outside the averaging region.

The boundary conditions of the problem come from the conditions of heat balance. On the surface $z = 0$ in the regions of solid, glass-like as well as a liquid and two-phase state, the condition has the form:

$$\lambda_i = \left.\frac{\partial\theta}{\partial z}\right|_{z=0} = (\alpha_k+\alpha_{r_i})(\theta|_{z=0}-\theta_{gl}), \quad i = 1, 2, 3... \tag{13}$$

Here α_k is the convective coefficient of heat transfer; θ_g is the gas temperature; α_{ri} is the radiation coefficient of heat transfer that satisfies the ratio

$$\alpha_{r_i} = \varepsilon_i\sigma_0(\theta|^2_{z=0}+\theta_g^2)(\theta|_{z=0}+\theta_g), \tag{14}$$

where ε_i, σ_0 is the set emissivity factor and Stephan–Boltzman constant, respectively.

For the intensity of laser radiation, we accept the normal Gaussian distribution law, and it depends on the change of z radius of the beam

$$r_z = \left(r_F^2+\left(\frac{z-Z_F}{\pi r_F}\lambda_0\right)^2\right)^{1\backslash 2}. \tag{15}$$

Here Z_F is the coordinate along z of the focal plane; r_F is the radius of laser beam in the focal plane; λ_0 is the laser radiation wavelength.

For the convenience of software realization of the calculating algorithm and its presentation, all the multifold of iterations in the external cycle is divided into stages. The calculated region G at the first stage of calculations is a rectangle in the plane of the plate joint. Its sides $z = 0$, $z = h$, $x = -l_1$, $x = l_2$, where l_1 and l_2 are distances respectively from the left and right boundaries of the rectangle to the axis of the laser beam. The choice of values l_1 and l_2 depends on the power of the laser and the speed of welding.

APPROXIMATION OF THE EQUATION

The region of solving the problem is covered with an irregular differential grid G_h with the nodes (ih_1, ih_2), $i = 0.1, \ldots, n_1$, $j = 0.1, \ldots, n_2$, where h_1 and h_2 are grid steps. For numerical solution of the problem, the variants of the scheme of the installation method were used. One of them for equation (11) has a form

$$\frac{\theta_{i,j}^{n+1} - \theta_{i,j}^{n}}{\tau} + \nu \frac{\theta_{i+1,j}^{n+1} - \theta_{i-1,j}^{n+1}}{2h_1} = \\ = \alpha_i \left(\frac{\theta_{i+1,j}^{n+1} - 2\theta_{i,j}^{n+1} + \theta_{i-1}^{n+1}}{h_1^2} + \frac{\theta_{i,j+1}^{n} - 2\theta_{i,j}^{n} + \theta_{i,j-1}^{n}}{h_2^2} \right) - \\ - \frac{\alpha_i}{l_\theta^2} (\theta_{i,j}^{n+1} - \theta_\alpha). \quad (16)$$

Except of it, the scheme of conditional approximation was also tested. We should note that in the calculated region, the convergence of a numerical solution was observed on the convergence of the value

$$\max_{i,j} \left| \theta_{i,j}^{n+1} - \theta_{i,j}^{n} \right|.$$

When using the second scheme, the value of the closing error from the substitution of the difference solution was additionally observed in the difference equation of thermal conductivity and difference conditions on the boundaries. In this case, naturally, in them fictitious derivatives in time were removed, and derivatives of spatial variables and nonhomogeneous terms were all copied on the last time layer. Iterations stopped as soon as these values became lower than some of the set values.

APPROXIMATION OF BOUNDARY CONDITIONS

The boundary conditions on the outer and inner boundaries (fronts between the phases of product material) are approximated with the first order. To record the boundary conditions at a specific point, it is necessary to have numerical values of the normal component and curvature of the boundary. Since all inner boundaries in the considered problem are certain isotherms, then when it is necessary, based on the calculated grid values of the temperature, the corresponding boundaries are found by interpolation. Boundary conditions also take into account a mobile nature of the source.

To accelerate the iterative process in all differential boundary conditions, a fictitious differential derivative of time from temperature was artificially added. Similarly, as in the equation (16), the sign in it was chosen so that the element module on the diagonal increased in the corresponding line of the matrix of the system of linear algebraic equations of the differential problem.

In the process of conducting one current iteration in the entire calculated region (global iteration), the system (16) is successively solved by passes along the axis x in all subregions. In the middle of the subregion, all possible values of j index are succesively changed in it. The values of solving on the boundaries of all subregions are taken from the previous iteration. After completion of iteration, the values of the solution in all nodes on the boundary of subregions are specified. In each node on the boundary, the boundary condition is solved relative to the temperature value in the selected node. Thus, its specified value is found through the value of temperature in the adjacent nodes obtained on the mentioned iteration. It is used on the next iteration as a value for solution on the boundary.

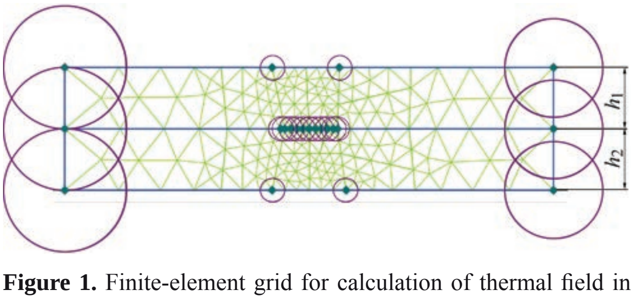

Figure 1. Finite-element grid for calculation of thermal field in polymer films during their laser welding

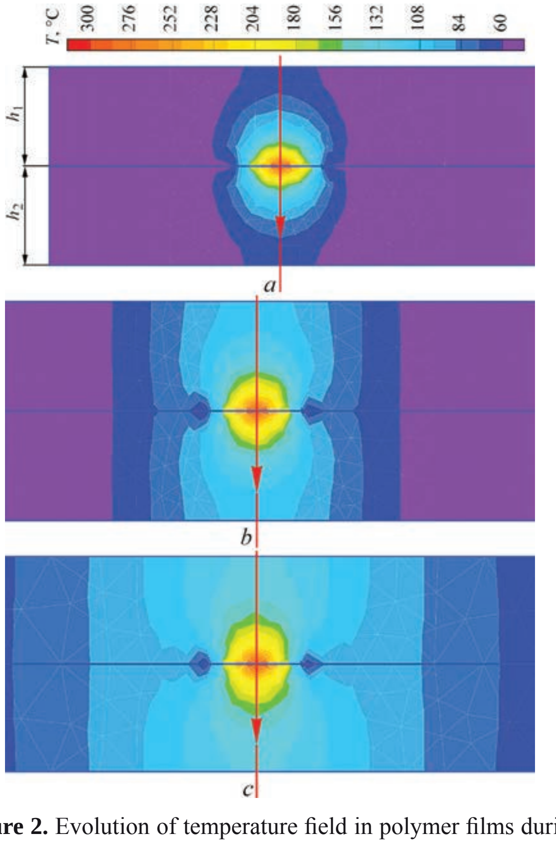

Figure 2. Evolution of temperature field in polymer films during their laser welding (static heating) a — $t = 1$; b — 3; c — 10 s. The arrow shows the direction of the laser beam (coordinate axis Y)

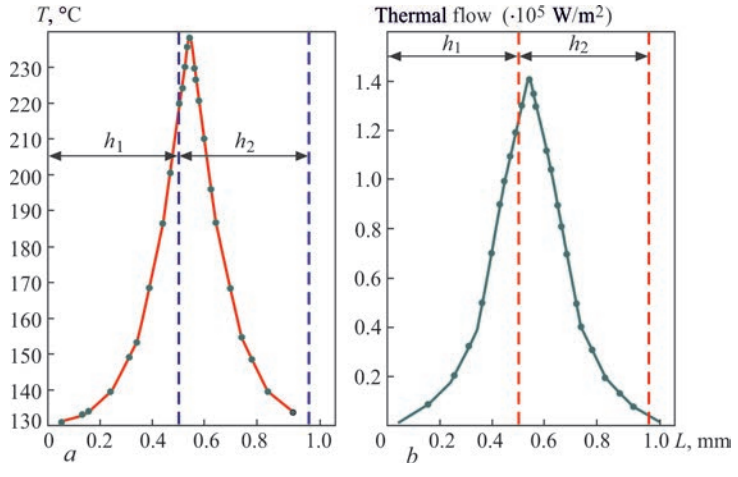

Figure 3. Distribution of temperature (*a*) and thermal flow (*b*) over thickness in the zone of joining films

In the mentioned calculations, such conditions considered to be satisfactory, when with a twice increase in the size of the region and independent refinement of the grid steps, the calculated values in the regions between the phases differed by not more than 3 %. In this problem, the required size of the calculated region, of course, depends on the speed of welding. The higher it is, the greater asymmetry in the isotherm pattern relative to the axis of the laser beam.

In addition, considering the specifics of the temperature behavior of polymer materials, the thermal conditions in the welding zone should be strictly controlled and maintained at a set level. As the calculations show, the most critical parameters of the mode at a set laser power is speed of welding and width of the temperature interval of the viscous flow state $\Delta\theta_{AO}$.

For numerical realization of defined equations, the finite elements method was used, which is based on the alternative formulation of the problem. Figure 1 shows a scheme of transmission welding model and an irregular finite element grid for calculation of the thermal field. The beginning of the Cartesian coordinate system is located in the center, circumferences show different sizes of grid elements. Thermal fields during welding of polyethylene films with a thickness of 0.2–0.5 mm by laser with a power of 10 W at a speed of 0.01–0.02 m/s were calculated.

Analysis of results from the diagrams of mathematical modeling (Figures 2–5) shows that in transmission laser welding, temperature distribution across the width of the weld is nonuniform, which is predetermined by the Gaussian distribution of power density in a laser beam. At a set laser power, more favorable conditions for the formation of a welded joint occur in the case of welding films, the upper of which has a lower thermal conductivity. The zone of maximum temperatures can be shifted due to conditions of heat transfer from the joint zone. The optimal conditions for the formation of a high-quality welded joint are the conditions under which the zone of maximum temperatures is localized in the contact area of welded films. Comparison of the results of theoretical and experimental studies shows that at set parameters of continuous welding mode, an optimum speed is a relative speed, at which heating is achieved at a depth of not less than 2/3 of the thickness of each part, counting from the plane of their physical contact.

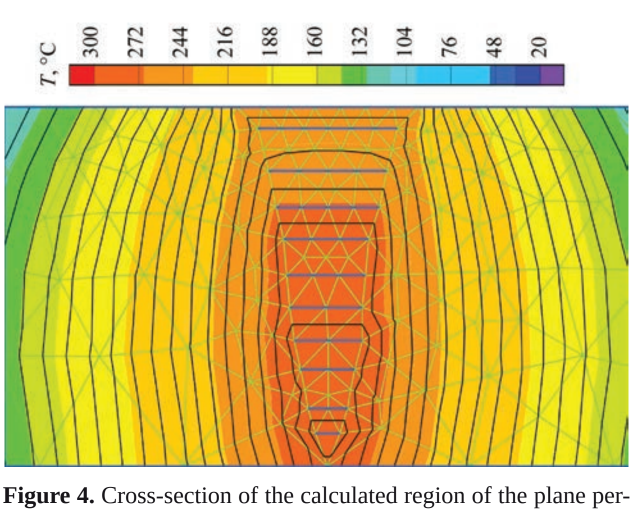

Figure 4. Cross-section of the calculated region of the plane perpendicular to the axis *x* at the point with the maximum width of the HAZ (Gaussian distribution in the laser beam)

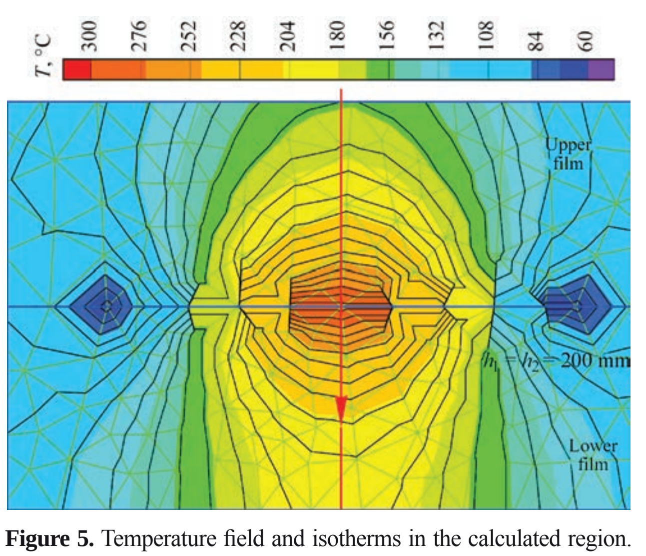

Figure 5. Temperature field and isotherms in the calculated region. The arrow shows the direction of the laser beam (coordinate axis *Y*)

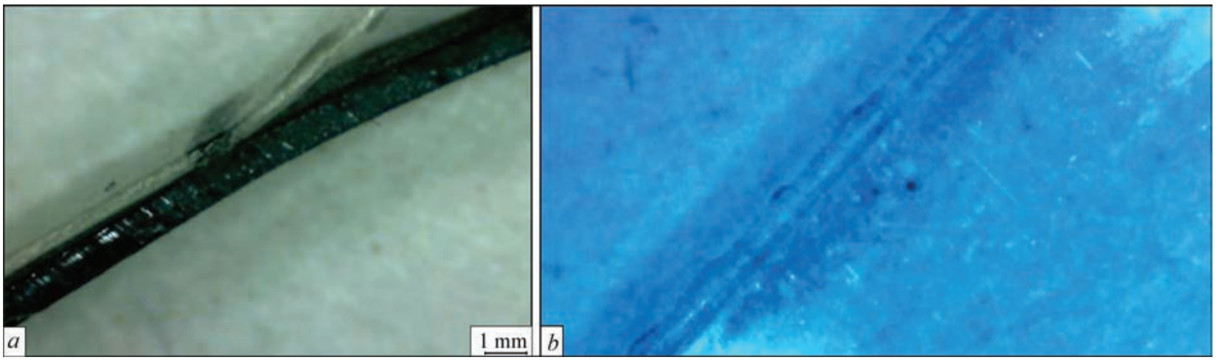

Figure 6. Appearance of welds produced using laser welding: *a* — weld of a transparent polyethylene film with a thickness of 0.5 mm, equal strength with the base material; *b* — sealed weld of a modified medical film with a thickness of 0.2 mm

Figure 6 shows the appearance of welds produced by laser welding taking into account the results of mathematical modeling of thermomechanical processes.

CONCLUSIONS

Modeling of thermal processes in transmission laser welding of sheet polymer materials was carried out. The main equations were formulated to describe heat release under the action of radiation to the surface for possible models of overall heat balance; point heat source; circular source; linear source. The mathematical model of heat transfer process during welding, described by the quasi-stationary equation of heat conductivity and nonlinear boundary conditions of thermal balance, was proposed. For numerical solutions of defined equations, the finite element method was used.

The results of mathematical modeling allowed investigating the features of the formation of thermal fields in transmission laser welding of polymer films at different parameters of welding mode. It was shown how depending on power and speed of the movement of radiation source, it is possible to adjust the thermal conditions in the zone of polymer joints taking into account their absorbing properties, temperature of transition to viscous flow state, thermophysical properties of the material, heat transfer conditions and other parameters.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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