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CALCULATION-EXPERIMENTAL INVESTIGATION OF THERMAL FIELDS IN THE PROCESS OF NONSTATIONARY SOLDERING

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In the work theoretical and experimental methods were used to investigate temperature fields in the conditions of soldering the metal plates, contacting with a heated body. To determine thermal conditions, necessary to provide soldering (melting of solder in the joint zone), calculation of temperature distribution with time in the joint zone was carried out, depending on characteristics of «heater-plate-solder-plate» system and thermal resistance in contacts between the system elements. It is shown that by comparing the theoretically calculated and experimentally measured thermograms, it is possible to determine thermal resistance in the contact zones. On the basis of the obtained values of thermal resistance in the contacts, the modeling of thermal fields in the systems with the arbitrary dimensions of elements was carried out. 13 Ref., 7 Figures.

Keywords: *thermal fields, non-stationary process, method of finite differences, reaction soldering, permanent joint, multilayer foil, local heating*

Brazing is widely used for production of permanent joints of parts [1, 2]. This process lies in heating of parts being joined in a furnace till brazing alloy melting (stationary conditions) or local heating of a joint zone with the help, for example, of a contact with earlier heated body or under effect on it of source of concentrated heat radiation (infrared [3], laser [4] etc.) [5]. Distribution of temperature fields in the joint zone under conditions of its local heating till brazing alloy melting temperature will have non-stationary nature, since heating will be accompanied by heat removal to cold areas of the parts being joined. If there is no limitation of power of concentrated heat sources, realization of this brazing process will not cause difficulties even under conditions of repair on large-size part surface, for example, in patching a shell of material with high heat conductivity (aluminum alloys).

In the case of absence of the concentrated heat sources and large area of the joint the heaters can be used for its heating. They generate heat energy as a result of initiation of exothermal reaction in them. Powder mixtures, components of which react with heat emission, can be used as such heaters. It is known that intensity of exothermal reactions significantly increases at transfer from powder mixtures to compact materials with composite structure on their basis. Thus, works [6, 7] show that multilayer foils can be used as such composite materials. They consists of layers based on intermetallic forming elements such, for example, as Ni and Al or Ti and Al, received by PVD [8]. Initiation of self-propagating high-temperature synthesis (SHS) reaction in such systems results in heat emission intensity reaching the value of around 5–6 kW/cm^2 [9] that can provide local heating of the joint zone under intensive heat removal conditions.

Schematically such a soldering process of the same size plates can be presented as it is shown on Figure 1 (laboratory system). In such a system heater characteristics, necessary for soldering process, can be determined in experimental way, varying the mass of reaction material. However, if such an approach to determination of the heater characteristics is applicable to the plates of one size then in the case, for example, of joining the plate of small (finite) size to the plate of larger (unlimited) size will cause difficulties. Mainly, it is related with the necessity to take into account heat removal from the joint zone into the large size plate using the results received on the finite size samples. It is clear that heater parameters should be increased in order to compensate this heat removal. Still, considering that the plates are made of aluminum alloys, increase of heater mass can results in their significant overheating. This will result in a degradation of mechanical properties of the plates. From this point of view selection of heater characteristics is the key for change of dimensions of the system elements being joined. Determination of the heater optimum characteristics, necessary for reaction soldering of the plates of random dimensions under conditions of local heating of the joint zone, could be fulfilled based on calculation of thermal fields.

At the same time, complexity of realization of this approach is caused by the fact that thermal processes in the joint zone depend on many parameters, some of them are known (for example, heat conductivity of materials being joined) or present themselves geometry and mass characteristics of the system elements, other have undetermined value, as, for example, a value of thermal resistance at contact boundary of the system elements. To eliminate this ambiguity in selection of the parameters for thermal field modelling in real systems the work proposes a method for calculation of coefficients of thermal resistance of the contacts, based on performance of comparison of experimentally measured and calculated change of temperature in finite dimension system (laboratory system). Satisfactory correspondence of the experimental and calculation data was received by means of variation of the parameters describing thermal resistance at elements' interface. This allows carrying modelling of the thermal fields under nonstationary conditions of soldering of limited size plate on the surface of unlimited size part.

Experimental and calculation methods. For description of a nonstationary process of heat distribution in 3D sample let's write down a heat conductivity equation in the following form:

$$c\rho \frac{\partial T}{\partial t} = div\left(\kappa \, \mathrm{grad}\, T\right), \tag{1}$$

where c is the heat capacity of the material; ρ is the density; κ is the heat conductivity coefficient.

Considering that the system consists of different materials, which have different nature of heat exchange between the separate areas, it is convenient to divide it on finite elements. A finite-difference method [10, 11] is used in the work to solve this equation. It allows determining temperature values in a finite element through the values of temperatures in neighbor ones and characteristics of material heat conductivity:

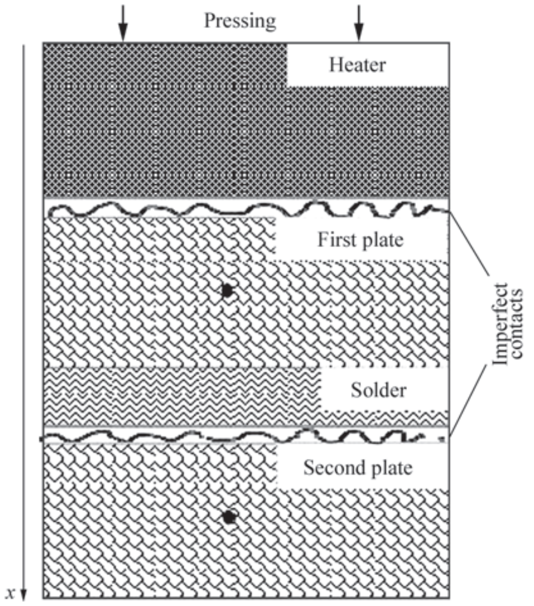

Figure 1. Scheme of obtaining the permanent joints of similar size plates (laboratory system) using soldering with the help of local heating of joint zone from external heater

$$T^{\mathrm{new}}_{i,j,k} = T_{i,j,k} + a_k^2 \left(\begin{array}{l} \dfrac{T_{i-1,j,k} - 2T_{i,j,k} + T_{i+1,j,k}}{dx^2} + \\ + \dfrac{T_{i,j-1,k} - 2T_{i,j,k} + T_{i,j+1,k}}{dy^2} + \\ + \dfrac{T_{i,j,k-1} - 2T_{i,j,k} + T_{i,j,k+1}}{dz^2} \end{array} \right) dt, \tag{2}$$

where $a_k^2 = \kappa / (c\rho)$ is the coefficient of temperature conduction; $T_{u,j,k}$ is the temperature of finite element in point $x_{i,j,k}$.

This finite difference scheme (2) can be used for all non-boundary areas of the system. The neighbor points in boundary elements will be characterized with significantly different heat conductivities or geometry/mass parameters. Therefore, record of a density of heat flow for boundary areas is more convenient in form of temperature differences instead of temperature gradients using at that some «heat transfer coefficient» μ rather than heat conductivity κ. For example, $J = -\mu_{i,i+1} \Delta T$ for cells i and $(i + 1)$ with heat conductivity coefficients κ_i, κ_{i+1} and cell size h_i, h_{i+1}.

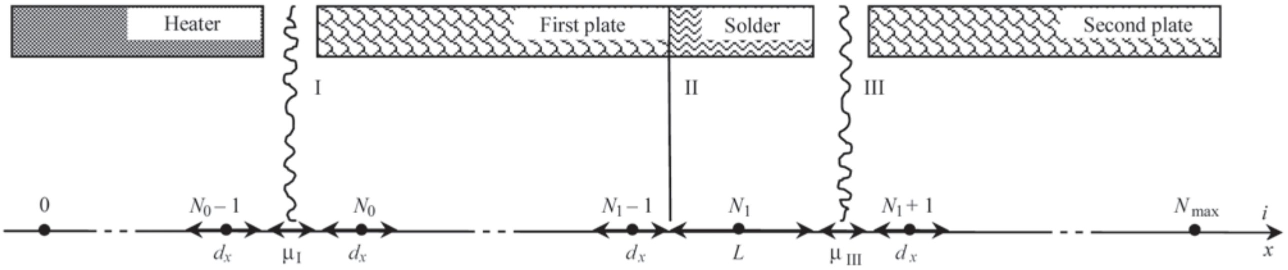

Figure 2. Scheme of division of system consisting of heater, first plate, solder and second plate on finite size plates (scheme corresponds to one-dimensional approximation)

$$\mu_{i,i+1} = \frac{2\kappa_i\kappa_{i+1}}{\kappa_i h_{i+1} + \kappa_{i+1} h_i}. \qquad (3)$$

Then for cells, having neighbor cells with other coefficients of heat conductivity or size, equation (2) is changed. In one-dimensional form it is written as

$$T_i^{\text{new}} = T_i + \frac{1}{c_i\rho_i h_i}\left(-\mu_{i-1.i}\left(T_i - T_{i-1}\right) + \mu_{i.i+1}\left(T_{i+1} - T_i\right)\right)dt. \qquad (4)$$

Figure 2 shows three contact zones, for which equation (4) is used:

I — between the heater and first plate (imperfect contact);

II — between the first plate and solder (ideal contact formed by means of vacuum phase deposition);

III — between the solder and the second plate (imperfect contact).

We would like to remind that imperfection of contact I means growth of thermal resistance and decrease of heat flow between the heater (cell $N_0 - 1$) and the first plate (N_0). Contact I is described by heat transfer coefficient μ_1, which in general case is uncertain quantity. Imperfection of contact III supposes thermal resistance between solder (cell N_1) and the second plate ($N_1 + 1$) (Figure 2) and is described by heat transfer coefficient μ_{III}, which is also uncertain parameter of the system. Since, as it was mentioned, contact II is an ideal, then for it the heat transfer coefficient is determined following the equation (3):

$$\mu_{N_1-1,N_1} = 2\kappa_{\text{plate1}}\kappa_{\text{solder}} / (\kappa_{\text{plate1}}L + \kappa_{\text{solder}}dx)$$

Change of the temperature from the left and right of the contact I is described by equations:

$$T^{\text{new}}_{N_0-1,j,k} = T_{N_0-1,j,k} + \begin{pmatrix} -\dfrac{a^2_{\text{heater}}}{dx^2}(T_{N_0-1,j,k} - T_{N_0-2,j,k}) + \\ + \dfrac{\mu_1 a^2_{\text{heater}}}{\kappa_{\text{heater}}dx}\left(T_{N_0,j,k} - T_{N_0-1,j,k}\right) \end{pmatrix} dt,$$

$$T^{\text{new}}_{N_0,j,k} = T_{N_0,j,k} + \begin{pmatrix} -\dfrac{\mu_I a^2_{\text{plate1}}}{\kappa_{\text{plate1}}dx}(T_{N_0,j,k} - T_{N_0-1,j,k}) + \\ + \dfrac{a^2_{plate1}}{dx^2}\left(T_{N_0+1,j,k} - T_{N_0,j,k}\right) \end{pmatrix} dt. \qquad (5)$$

Contacts II and III refer to the solder, which is in solid state at low temperatures $T < T_{\text{out}}$, liquid at $T > T_{\text{out}}$ and preserve constant temperature T_{out} at rising portion of liquid phase η in process of melting. Therefore, it is convenient to enter temporary variables T_{XL}, T_{XR} for the left and right boundary of the solder. Using a condition of continuity of the heat flows the following can be found in these boundaries:

$$T_{XL} = \frac{(\kappa_{\text{solder}}dxT_{N_1,j,k} + L\kappa_{\text{plate1}}T_{N_1-1,j,k})}{L\kappa_{\text{plate1}} + \kappa_{\text{solder}}dx},$$

$$T_{XR} = \frac{(L\mu_{III}T_{N_1+1,j,k} + 2\kappa_{\text{solder}}T_{N_1,j,k})}{2\kappa_{\text{solder}} + L\mu_{III}}. \qquad (6)$$

Then the heat flows to solder and from it:

$$J_{\text{in}} = -2\kappa_{\text{plate1}}\kappa_{\text{solder}}\frac{(T_{N_1,j,k} - T_{N_1-1,j,k})}{L\kappa_{\text{plate1}} + \kappa_{\text{solder}}dx},$$

$$J_{\text{out}} = -\frac{\mu_{III}\dfrac{2\kappa_{\text{solder}}}{L}}{\mu_{III} + \dfrac{2\kappa_{\text{solder}}}{L}}(T_{N_1+1,j,k} - T_{N_1,j,k}), \qquad (7)$$

where J_{in}, J_{out} are the input and output heat flows for solder cell (we describe it using only one cell, which at low temperatures correspond to solid state, at high to liquid ones, and in intermediate period to double phase system solid body-liquid with eutectic temperature).

When solder temperature is lower than the eutectic temperature (solid solder) or higher (liquid), it is determined by equation

$$T^{\text{new}}_{N_1,j,k} = T_{N_1,j,k} + (J_{\text{in}} - J_{\text{out}})dt / c_{\text{solder}}\rho_{\text{solder}}dx. \qquad (8)$$

Then the heat flow into the solder as well as from it will be described in the following way:

$$\eta^{\text{new}} = \eta + (J_{\text{in}} - J_{\text{out}})dt / \lambda L\rho_{\text{solder}}, \qquad (9)$$

where L, λ, ρ are the thickness of solder layer, specific heat of melting and density, respectively.

Solder heat conductivity coefficient κ_{solder} varies as $\kappa_{\text{solder}} = \kappa^{\text{liquid}}_{\text{solder}}\eta + \kappa^{\text{solid}}_{\text{solder}}(1-\eta)$ in accordance with change of content of liquid and solid phase. Moreover, we suppose that after complete melting of solder thermal resistance between it and the second plate is significantly reduced (i.e. heat transfer coefficient $\mu^{\text{new}}_{\text{III}}$ rises) due to increase of area of a contact surface of liquid solder with a surface of the second plate. Taking this in account, change of μ_{III} coefficient after melting beginning can be presented in form of

$$\mu^{\text{new}}_{\text{III}} = \kappa_{\text{plate 2}} \times$$
$$\times\left(\mu_{\text{solid}}(1-\eta) + \eta\frac{2\kappa^{\text{liquid}}_{\text{solder}}}{L}\right) \Big/ \left(\kappa_{\text{plate 2}} + \frac{\eta\kappa^{\text{liquid}}_{\text{solder}}dx}{L}\right), \qquad (10)$$

where μ_{solid} is the coefficient of heat transfer between solid phase of solder and second plate. In a limiting case $\eta = 0$ equation (10) comes to $\mu^{\text{new}}_{\text{III}} = \mu_{\text{solid}}$. In the other limiting case it is simplified into

$$\mu^{\text{new}}_{\text{III}} = \frac{2\kappa_{\text{plate 2}}\kappa^{\text{liquid}}_{\text{solder}}}{L\kappa_{\text{plate 2}} + \kappa^{\text{liquid}}_{\text{solder}}dx},$$

i.e. matches with the general equation (3). As a consequence, equation (3) can be written for the final boundary cells of the system, if consider that existence of imperfect contacts between the different elements leads to appearance of thermal resistance, and solder melting takes place at some temperature. This approach is described in more details in work [12]. Its application allows calculating temperature distribution at each moment of time depending on system parameters and in such a way trace change of temperature in a set point of the system.

It is necessary to compare calculated values of temperature with experimentally measured for checking this approach used in description of the thermal fields in a nonstationary soldering mode. A system consisting of a heater and two plates of AMg6 alloy of 5 mm thickness and 50×50 mm size, divided by solder (eutectic alloy Al–Si) layer (100 μm) deposited on the first plate, was investigated for this purpose. A multilayer Al/Ni foil was used as a heater. It was located over the first plate and pressed with set force (about 1000 N). After that SHS reaction accompanied by intensive heat emission was initiated in a nanofoil using current pulse. Redistribution of heat from the heater to the plates resulted in system heating to necessary temperature. Temperature was measured using two thin thermal couples established in the plate center (Figure 1). The thermocouples were connected to computer by ADC with sampling frequency 1 kHz. Received data were used to determine model parameters.

Results and discussion. Calculations of thermal fields of the system were carried out to determine solder melting conditions. They were based on characteristics of used materials and their thickness, at variation of heater thickness d_n. Figure 3 presents the calculated variations of the temperature in the first plate, received taking into account an assumption that rate of SHS reaction in the heater is significantly larger than heat distribution. This assumption is based on the fact that time of «burning» of 5 mm thick foil makes 0.05 s [13] at 100 cm/s rate of front distribution in SHS reaction. In this case characterization of the heater was grounded on its geometry and temperature, which it reaches as a result of SHS reaction. The time of its heating to maximum temperature was neglected at that. It can be seen that increase of heater thickness promoted rise of the maximum heating temperature of the first plate and all system in whole (the calculations were carried out in adiabatic conditions). If solder melting temperature is set then the system can be heated to necessary level by increase of heater thickness d_n. For example, 3 mm thick heater provides melting of solder with 700 K melting temperature (Figure 3) that effects the dependence of temperature in the center of first plate on time of contact with heater (calculation data) in form of «shelf». It should be noted that temperature of the «shelf» is somewhat higher than temperature of solder melting, moreover, this difference rises at increase of heater thickness (its heating value) as a consequence of temperature gradient present in the first plate, which is increased normal to heating rate.

It can be supposed that the heating rate of the first plate will significantly depend on thermal resistance of the contact between the heater and the first plate. Figure 4 presents calculation data at similar thickness of heater (3 mm), but with different value of thermal resistance in the contact between the heater and the first plate. It can be seen that change of the thermal resistance value significantly varies heating rate that is reflected in solder melting time, i.e. time till complete melting of solder rises from 5 to 30 s at thermal resistance increase by order.

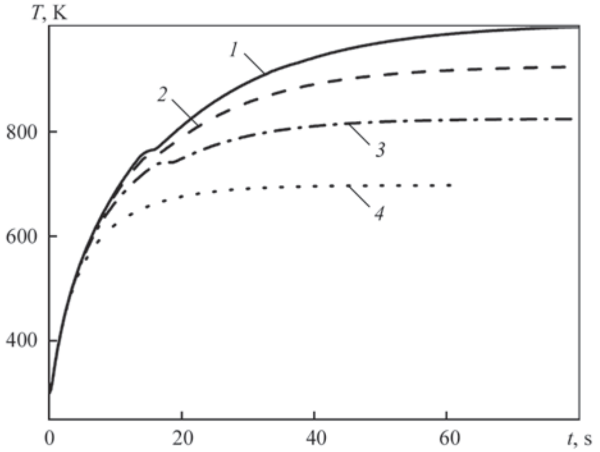

Figure 3. Effect of heater thickness on kinetics of temperature change in the center of first plate: *1* — d_n = 5 mm; *2* — 4; *3* — 3; *4* — 2

Since solder temperature and level of its melting are the result of heat balance between a heat flow from the heater into the first plate and heat flow from the solder into the second plate, it can be supposed that thermal resistance at the interface between the solder and the second plate will also effect the change of solder temperature. In fact, as can be seen from Figure 5, rise of heat conductivity in the contact zone between the solder and the second plate leads to delay of heating of the first plate, and, respectively, solder. However, regardless the fact that decrease of heat conductivity at the boundary between the solder and the second

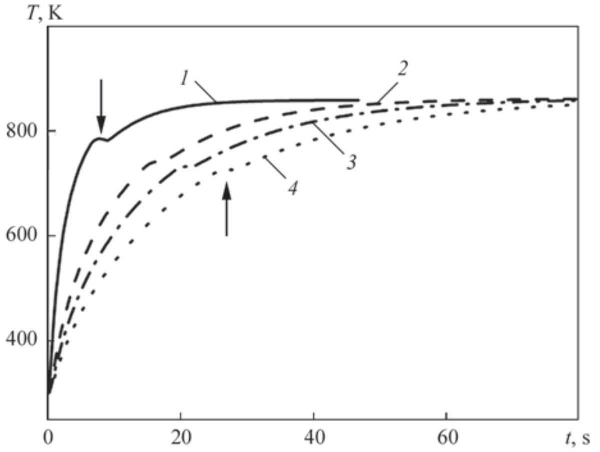

Figure 4. Dependence of temperature of first plate on time at different characteristics of heat resistance at heater – first plate interface: *1* — $\mu_0 = 5\cdot10^4$ W(m$^2\cdot$K); *2* — $1\cdot10^4$; *3* — $7\cdot10^4$; *4* — $5\cdot10^3$. Characteristics of heat conductivity of solder and second plate contact are constant (arrows indicate peculiarities of temperature change promoted by solder melting (its completion))

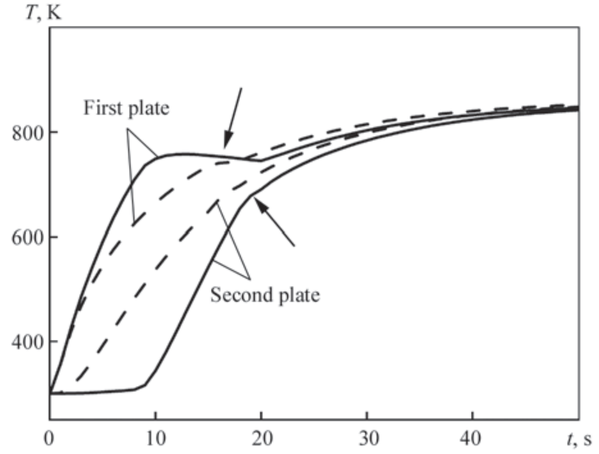

Figure 5. Dependence of temperature in the middle of plates on time at different characteristics of heat resistance at solder — second plate interface: $\mu_1 = 5\cdot10^2$ (*solid line*); $5\cdot10^4$ W/(m^2·K) (*dashed*). Characteristics of heat conductivity of contact of heater and first plate are constant (designation of arrows is the same as in Figure 4)

plate results in earlier solder melting, time till its end rises. It can be observed from temperature to time dependence in a middle of the second plate (Figure 5) that solder melting is finished when its temperature reaches solder melting temperature.

Proceeding from the fact that soldering process takes place under condition of complete melting of solder, the results of calculations indicate that the value of heat conductivity of the contact between the solder and the second plate does not have significant effect on time of this process completion.

Figure 6 presents the calculation and experimental data in the system described above, measured with the help of thermal couples, fixed in the middle of first and second plates. It can be seen that temperature of the first plate, contacting with the heater dramatically rises from the moment of SHS reaction start in the heater. However, in 8–9 s heating rate of the first plate dramatically changes. During this time temperature of the first plate and attached to it solder reaches solder melting temperature (around 700 K). Based on this it can be supposed that a delay of temperature growth in the first plate is caused by solder melting.

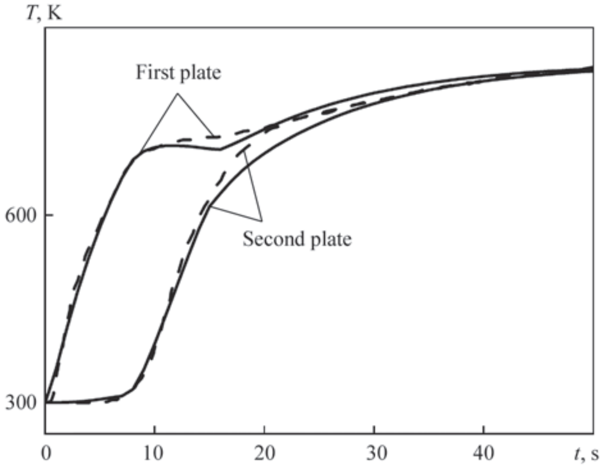

Figure 6. Experimentally measured (*dashed line*) and calculation (*solid line*) temperature in the middle of first and second plates in soldering at their local heating with the help of heater being in contact with first plate

In favor of this is the evidence of a point of start of temperature increase in the second plate. Such a delay in heating time of the second plate can be explained by high thermal resistance in the contact between solder and second plate. After solder melting a heat contact between it and the second plate is improved that promotes redistribution of heat from solder to the second plate and its heating to the temperature level of the first plate.

Change of temperature in the system in process of its heating, qualitatively similar to that is observed experimentally (Figure 6), was calculated by means of variation of parameters of heat resistance in the contacts. At that it was supposed that heat resistance at the interface between the solder and the second plate will disappear in the moment of solder melting.

Based on this it was assumed that the calculated parameters of heat resistance in the contacts under these conditions of soldering process can be used for calculation of temperature fields in the case when the first plate is connected to the second plate, size of which is significantly larger, i.e. for 3D case.

Figure 7 represents the temperature distribution in a cross-section of the system, consisting of heater, first plate with deposited solder and second plate of larger size in the moment when solder temperature reaches the temperature of its melting (condition necessary for soldering). It can be seen that heat exchange between the system elements results in heat distribution from the heater to the first plate and then through the solder to the second plate. In contrast to laboratory assembly in this case heat is distributed along the second plate outside the dimensions of the first plate. However, as can be seen from Figure 7, such a «spread» of heat in a volume of the second plate is not critical from point of view of achievement of temperature conditions for soldering in the contact between the first and second

Figure 7. Distribution of temperature in cross-section of system (1/4 of its part is shown) at its local heating in the moment of solder melting. Length and width of second plate 3 times exceed length and width of first plate

plates. The calculations showed that only 10–20 % increase of heater thickness is enough to compensate these heat losses in the case of joining the plates of equal thickness.

Conclusions

1. The calculation of thermal fields in soldering under nonstationary heating conditions with the help of local heat source of limited energy capacity showed that there is principal possibility to achieve melting of solder in form of thin interlayer between two plates with high heat conductivity.

2. It is shown that under adiabatic conditions the soldering time, necessary for melting of solder between the plates, significantly depends on parameters of heat contact between the heater and the first plate, but almost does not depend on parameters of heat contact between the solder and the second plate.

3. Their values can be determined based on experimentally measured thermograms for laboratory system, consisting of the elements with similar contact areas by means of self-consistent calculation including variation of parameters, characterizing heat resistance in the contacts.

4. Obtained parameters of heat resistance can be used in modelling of thermal fields in the systems for soldering of parts with random dimensions. It is shown that 10–20 % increase of energy capacity and, thus, thickness of heater, is necessary to achieve solder melting at transfer from laboratory to «real» system with «endless» second plate.

1. Merzhanov, A.G., Borovinskaya, I.P. (1972) Self-propagating high-temperature synthesis of refractory inorganic compounds. *Dokl. Akad. Nauk SSSR*, **204**, 366–369 [in Russian].
2. Sytschev, A.E., Vadchenko, S.G., Boyarchenko, O.D. et al. (2013) SHS welding by thermal explosion: Ti–Ti and Ti–NiAl joints. *Int. J. of Self-Propagating High-Temperature Synthesis*, 22(**2**), 99–102.
3. Ren-Kae Shiue, Chen Chia-Pin, Wu Shyi-Kaan (2015) Infrared brazing of Ti50Ni50 shape memory alloy and 316L stainless steel with two silver-based fillers. *Metallurg. and Mater. Transact. A*, 46(**6**), 2364–2371.
4. Nothdurft, S., Springer, A., Kaierle, S. et al. (2016) Stonis-Laser soldering and brazing of steel-aluminum sheets for tailored hybrid tubes. *J. of Laser Applications*, 28, **2**, https:doi.org/10.2351/1.4943996.
5. Jacobson, D.M., Humpston, G. (2005) *Principles of brazing*. USA.
6. Morsi, K. (2001) Review: Reaction synthesis processing of Ni–Al intermetallic materials. *Mater. Sci. & Engin. A*, 299(**1–2**), 1–5.
7. Weihs, T., Barmak, K., Coffey, K. (2014) Fabrication and characterization of reactive multilayer films and foils. *Metallic Films for Electronic, Optical and Magnetic Applications: Structure, Processing and Properties*, **40**, 160–243.
8. Ustinov, A.I., Olikhovska, L.O., Melnichenko, T.V., Shyshkin, A.E. (2008) Effect of overall composition on thermally induced solid-state transformations in thick EB PVD Al/Ni multilayers. *Sur. and Coat. Tech*., **202**, 3832–3838.
9. Kravchuk, M.V., Ustinov, A.I. (2015) Influence of thermodynamic and structural parameters of multilayer foils on SHS process characteristics. *The Paton Welding J*., **8**, 8–13.
10. Farlow, S. (1985) *Partial differential equations for scientists and engineers*. Moscow, Mir [in Russian].
11. Tikhonov, A.N., Samarsky, A.A. (1977) *Equations of mathematical physics*. Moscow, Nauka [in Russian].
12. Bezpalchuk, V.M., Zaporozhets, T.V., Kravchuk, M.V. et al. (2015) Calculation of thermal fields in multiphase 3D system under nonstationary conditions of its heating. *Visnyk ChNU*, 349(**16**), 38–49 [in Ukrainian].
13. Zaporozhets, T.V., Gusak, A.M., Ustinov, A.I. (2010) SHS reactions in nanosized multilayers – analytic model versus numeric model. *Int. J. of Self-Propagating High-Temperature Synthesis*, 19(**4**), 227–236.

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