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CALCULATION OF THERMAL FIELDS DURING JOINING ALUMINIUM PLATES THROUGH INTERLAYERS AT LOCAL HEATING OF THE JOINT ZONE

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The work presents the results of numerical modeling of thermal fields in the zone of joining aluminium plates through interlayers during local heating of the joint zone by a flat heater, contacting one of the plates. Layers consisting of braze alloy, multilayer reactive foil or layers of both types were considered as an interlayer. Calculation was carried out considering the thermal-physical characteristics of the material of plates, interlayer and heater, consisting of multilayer reactive foils, in which a reaction of self-propagating high-temperature synthesis is accompanied by intensive heat evolution. Conditions of local heating of the aluminium plates necessary for obtaining permanent joints during their brazing or welding through an interlayer were studied. 14 Ref., 1 Table, 11 Figures.

Keywords: *brazing, welding, aluminium alloys, braze alloy, multilayer foil, thermal fields, local heating, permanent joint*

Searching for new approaches for elimination of damage in shell-type structures from aluminium alloys under the conditions of limited access to powerful heat sources is an urgent task, the solution of which will allow increasing structure reliability and operating life [1–3]. From this viewpoint, it appears to be a promising idea to join an aluminium coverplate to the damaged area of the shell surface due to local heating of the joint zone by a heat source ensuring heating of the joint zone up to temperatures, at which conditions are in place, which are needed for joint formation, for instance, melting of a layer of braze alloy, located in the joint zone, or melting of the surfaces being joined.

It is known that reactive materials, which are capable of generating heat during running of the reaction of self-propagating high-temperature synthesis in them (SHS), can be used as the heat source, which in the self-supporting mode can provide the required conditions for welding or brazing of materials [4–6]. At local heating of the joint zone, the heat can be dissipated to the environment and propagate through the structural elements. To ensure heating of the joint zone, it is preferable to use materials with a high rate of heat generation.

As the intensity of heat generation in such materials essentially depends on the rate of SHS reaction running in them, application for these purposes of thermit mixtures seems to be less effective, compared to multilayer foils (MF), consisting of highly reactive materials. In thermit mixtures the rate of SHS reaction propagation is low, because of the small area of contact between the powder components and presence of oxide films on their surface [7]. In the case of MF the reactive layers contact each other over the entire foil surface that ensures the rate of SHS reaction front propagation by 1–2 orders higher, compared to powdered thermit mixtures [8–10]. Such properties of reactive MF allow applying them both as an interlayer for preheating the surfaces of aluminium plates being joined, and as a heater, contacting one of the plates (coverplate), for local heating of the joint zone.

At the same time, in order to apply such an approach to producing permanent joints, it is necessary to take into account the fact that the heat flow, continuously coming from the heater through the coverplate into the joint zone, is removed from it via the second plate (shell). If for instance, a braze alloy interlayer is located in the joint zone, it is important to establish not just the lower power limit of the heater, at which the braze alloy can be melted, but also not exceed the upper limit, at which the coverplate material, contacting the heater, can be surface-melted.

It is clear that heat propagation in such systems is influenced both by thermophysical properties of the material of system elements, and heat transfer (thermal resistances) on the boundaries between them. Here, the thermophysical parameters are usually known, whereas the parameters of heat transfer between the system elements significantly depend on a number of factors (surface roughness, force of their

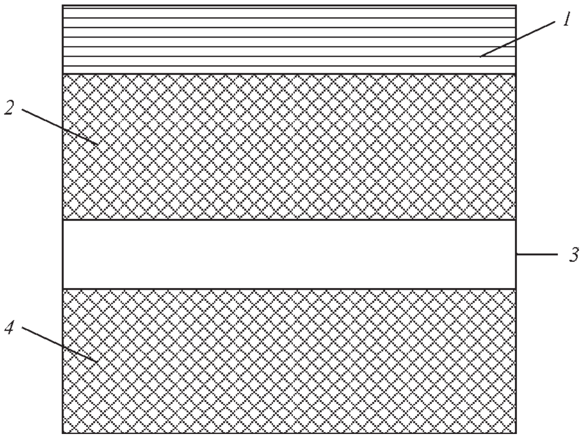

Figure 1. Scheme of joining plates at their heating as a result of contact of coverplate with heater: *1* — heater; *2* — coverplate; *3* — interlayer, *4* — shell in the form of plate

pressing to each other, etc.), which can vary in a broad range. Therefore, it is difficult to perform calculation of thermal fields in such systems in the general case. Earlier conducted investigations of temperature fields under the conditions of nonideal contacts between the system elements, showed [11] that the time of heat redistribution under such conditions is significantly longer. However, general regularities of the change of temperature fields are similar.

In this connection, it was assumed that contacts between the system elements are ideal, in order to clarify the effect of thermophysical characteristics of the studied system materials on thermal fields during joining of aluminium plates through interlayers based on the layers of braze alloy or multilayer highly reactive foil. This allowed clarifying the maximum permissible values of the parameters of the heater with a high rate of heat generation, providing the thermal conditions for producing permanent joints of aluminium plates.

Method of calculation of thermal fields. Scheme of joining plates through an interlayer by local heating of the joint zone through contact of the heater with one of the plates (furtheron referred to as coverplate), is shown in Figure 1. If heater *1*, for instance, of 0.05×0.05 m^2 size, consists of a pack of MF based on Ni and Al layers with equiatomic ratio of elements, characterized by a high rate of running of synthesis reaction, of the order of 1–3 m/s [8], ensuring its heating up to a certain (adiabatic) temperature, characteristic of MF chemical composition and structure over a short time of the order of 0.005–0.015 s, then the time of heater heating up to maximum temperature can be neglected.

Analysis of thermal fields was performed, proceeding from the fact that in the joint zone heating of the surfaces being joined should reach a temperature, which enables running of the processes, required for formation of a permanent joint between these surfaces. So, for joining plates by brazing, the temperature in the contact zone should be higher than the braze alloy melting temperature, and in the case of welding, it should be higher than the melting temperature of plate material.

Analysis of thermal fields was performed in the case of joining aluminium plates from AMg6 alloy. Considered as the heat source, is a pack consisting of MF based on Ni and Al layers with equiatomic element ratio. Similar MF were considered as interlayers for local heating of the joint zone. Used as the braze alloy was a model alloy of eutectic composition with melting temperature of 850 K. Thermophysical characteristics of materials in the system of «heater–coverplate (1st plate)–interlayer-2nd plate (shell)» are shown in the Table.

At modeling the thermal fields in aluminium plate joint zone, layers of braze alloy, MF and presence of layers of both types were considered as interlayers. If we assume that all the system elements have an unlimited size along two coordinates, parallel to the joint plane and limited size in the normal direction, it allows analyzing heat redistribution only in one direction, namely normal to the contact plane.

Characteristics of materials of «heater–coverplate–interlayer–shell» system

Parameters. Properties	Material			
	Multilayer foil Ni/Al (heater)	Aluminium alloy AMg6 (coverplate and 2nd plate (shell))	Model braze alloy (interlayer)	Multilayer foil Ni/Al (interlayer)
Thickness, mm	1–16	5–17	0.1	0.05–0.35
Specific weight, kg/m^3	5164	2650	2650	5164
Heat conductivity, W/m·K	51	126	155	51
Adiabatic temperature of SHS reaction, K	1912	–	–	1912
Braze alloy melting temperature, K	–	–	850	–
Latent heat of melting, kJ/kg	–	400	555	–
Heat of intermetallic formation, eV	0.46	–	–	0.46
Period of layer modulation in multilayer foil, nm	100	–	–	100
Multilayer foil thickness, μm	200	–	–	50–350
Energy of activation of interdiffusion between Al and Ni layers, eV	1.69	–	–	1.69

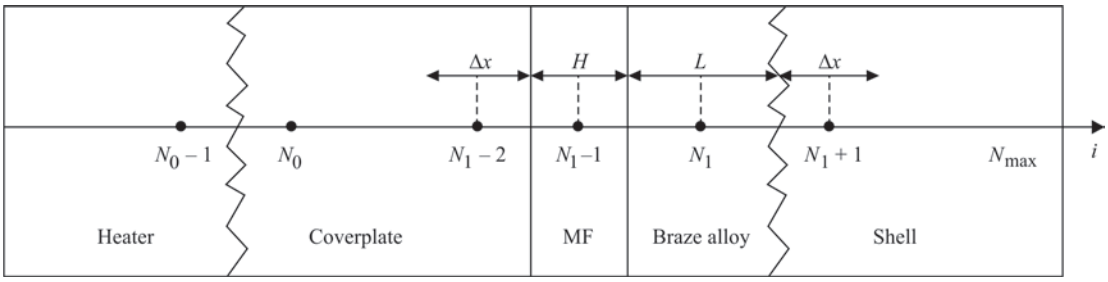

Figure 2. Scheme of division of «heater–coverplate–interlayer–shell» system into cells

All the system elements were divided into cells of a finite thickness Δx, except for the interlayer, which was regarded as one cell of thickness L, in the case of an interlayer based on braze alloy, or thickness H — for reactive MF, and two cells of thickness $L + H$, if the interlayer consists of a layer of braze alloy and MF. All the calculations were performed at system division into cells of 200 μm thickness. Cell numbering is shown in Figure 2.

Assuming that thermal energy radiation outside the system is absent, boundary conditions of the second kind will be satisfied for the extreme cells:

$$T_0 = T_1,\ T_{N_{\max}} = T_{N_{\max}-1}.$$

where $N_{\max}$ is the maximum cell number:

$$N_{\max} = L_0/\Delta x + L_1/\Delta x + L_2/\Delta x + 2,$$

where L_0 is the heater thickness; L_1 is the coverplate thickness; L_2 is the shell thickness.

To determine the temperature in each shell, it is necessary to solve the equation of heat conductivity

$$\frac{\partial T}{\partial t} = a\frac{\partial^2 T}{\partial x^2} \tag{1}$$

allowing for thermophysical properties of cell materials, where a is the thermal diffusivity of cell material.

Equation of heat conductivity (1) has a solution for all the system cells of width Δx:

$$T_i = T_i^{\text{old}} + a\frac{T_{i+1}^{\text{old}} - 2T_i^{\text{old}} + T_{i-1}^{\text{old}}}{\Delta x^2}dt, \tag{2}$$

where T_i is the temperature of the i-th cell, which it reaches within dt seconds, compared to initial temperature T_i^{old}. This ratio is valid for all the cells, except for $N_0 = 1$, N_0, $N_1 - 2$; N_1 and $N_1 + 1$, which belong to different system elements. In order to determine the temperature in the cells on the contact boundary, it was assumed that the heat flow is proportional to temperature difference in boundary cells i and $i + 1$, heat transfer between which is characterized by effective «coefficient of heat transfer» $\mu_{i,j+1}$, in keeping with relationship

$$J_{i,i+1} = -\mu_{i,i+1}(T_{i+1} - T_i).$$

In the case of an ideal thermal contact between cells i and $i + 1$, belonging to different system elements with coefficients of heat conductivity of their material k_i and k_{i+1}, thickness h_i and h_{i+1} respectively, the coefficient of heat transfer is defined as

$$\mu_{i,i+1} = \frac{2k_i k_{i+1}}{k_i h_{i+1} + k_{i+1} h_i}. \tag{3}$$

Then, equation (2) for determination of temperature in boundary cells can be found from the system of equations, which take into account the heat flows between the boundary and adjacent cells.

$$\begin{aligned} \frac{dT_i}{dt} &= \frac{1}{c_i\rho_i}\left(J_{i-1,i} - J_{i,i+1}\right), \\ \frac{dT_{i+1}}{dt} &= \frac{1}{c_{i+1}\rho_{i+1}}\left(J_{i,i+1} - J_{i+1,i+2}\right), \end{aligned} \tag{4}$$

where c_1 and ρ_i is the heat capacity and specific weight of the material of i-th cell.

As the heat source can have a temperature, which exceeds the melting temperature (T^{melt}) of coverplate material, the possibility of its partial or complete melting should be taken into account. Let at partial melting of the plate the boundary between the liquid and solid phases be located in point $\xi(x_N < \xi < x_{N+1})$ (Figure 3). Then temperature distribution to the left and right of the boundary can be calculated from the balance of heat flows, allowing for the fact that during time dt the boundary will shift by value dy.

$$J_1^Q S dt - J_s^Q S dt = \lambda\rho_{\text{pl1}} S dy, \tag{5}$$

where λ_{pl1}, λ_{pl2}, ρ_{pl1}, ρ_{pl2} are the specific heat of melting and density of plate material; S is the cross-sectional area; dy is the change of the boundary position.

Allowing for the coefficients of heat transfer in the liquid (l) and solid (s) phases, equation (5) can be written as

$$\frac{dy}{dt} = \frac{J_1^Q - J_s^Q}{\lambda\rho_{\text{pl1}}} = \frac{\kappa_1^{\text{l}}\left.\frac{\partial T}{\partial x}\right|^{\text{l}} + \kappa_1^{\text{s}}\left.\frac{\partial T}{\partial x}\right|^{\text{s}}}{\lambda\rho_{\text{pl1}}}. \tag{6}$$

Then the change of temperature of cells N' and $N' + 1$ during time dt can be calculated, proceeding from equations

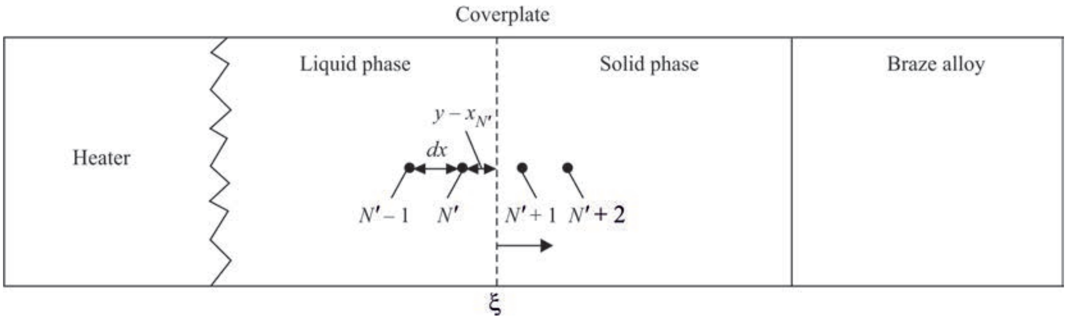

Figure 3. Schematic image of the interface of the liquid and solid parts of the plate during its melting

$$\frac{T_{N'}^{\text{new}} - T_{N'}^{\text{old}}}{dt} = a_{\text{pl1}}^{\text{l}} \frac{\dfrac{T^{\text{melt}} - T_{N'}}{\xi - x_{N'}} - \dfrac{T_{N'} - T_{N'-1}}{dx}}{\dfrac{(\xi - x_{N'-1})}{2}}, \quad (7)$$

$$\frac{T_{N'+1}^{\text{new}} - T_{N'+1}^{\text{old}}}{dt} = a_{\text{pl1}}^{\text{l}} \frac{\dfrac{T_{N'+2} - T_{N'+1}}{dx} - \dfrac{T_{N'+1} - T^{\text{melt}}}{x_{N'+1} - \xi}}{\dfrac{(x_{N'+2} - \xi)}{2}}. \quad (8)$$

Such calculations should be performed at each time step, simultaneously following the position of the boundary. We will calculate the new position of the boundary of the liquid and solid phases from the following formula:

$$\xi^{\text{new}} = \xi + \frac{dt}{\lambda \rho_{\text{pl1}}} \times \left(\kappa_1^{\text{s}} \frac{T_{N'+1} - T^{\text{melt}}}{x_{N'+1} - \xi} - \kappa_1^{\text{l}} \frac{T^{\text{melt}} - T_{N'}}{\xi - x_{N'}} \right), \quad (9)$$

Temperature of plate cells, which are located to the left and right from the interface (except for near-boundary layers) is calculated by formula (4), but with different heat conductivity: κ_1^{l} for the molten part and κ_1^{s} for the solid part of the plate.

In the case, when the braze alloy, located in the gap between the plates, is partially melted, the equations for temperature calculations in the adjacent cells will be similar (5)–(9), just the heat conductivity κ_1^{s} inherent to the solid phase of the braze alloy, should be changed to the heat conductivity κ_1^{l} of the liquid phase.

At partial melting of the braze alloy, the position of liquid-solid phase boundary can be described by parameters η (0 < η < 1), as shown in Figure 4.

Heat losses/contribution at melting/solidification can be allowed for from the difference in the heat flows. Heat change can be recalculated to the fraction of the melt in the vicinity of the plate cell

$$\left(J_{\text{in}}^{Q} - J_{\text{out}}^{Q} \right) dt = S \rho_{\text{br}} \lambda_{\text{br}} L d\eta, \quad (10)$$

where λ_{br} is the specific heat of melting of braze alloy; ρ_{br} is the braze alloy density; S is the cross-sectional area; L is the thickness of braze alloy layer; $d\eta$ is the change of molten braze alloy fraction; J_{in}^{Q}, J_{out}^{Q} are the heat flows entering and leaving the molten braze alloy, respectively.

Magnitude of heat flows on the boundaries between the cell contacting the molten braze alloy and the braze alloy, and the one between the braze alloy in the solid phase and adjacent cell of the shell can be written as

$$J_{\text{in}}^{Q} = -S \kappa_1^{\text{s}} \frac{T_x - T_{N_1}}{dx/2}, \quad (11)$$

$$J_{\text{out}}^{Q} = -S \mu_1 \left(T_{N_{2+1}} - T_{evt} \right). \quad (12)$$

where T_{evt} is the braze alloy melting temperature.

Temperature value on the boundary between the plate and the melt can be determined from the equality of heat flows from the plate into the braze alloy melt and from the melt into the solid phase of braze alloy

$$-\kappa_1^{\text{s}} \frac{\left(T_x - T_{N_1} \right)}{dx/2} = -\kappa_1^{\text{l}} \frac{\left(T_{evt} - T_x \right)}{\eta L}. \quad (13)$$

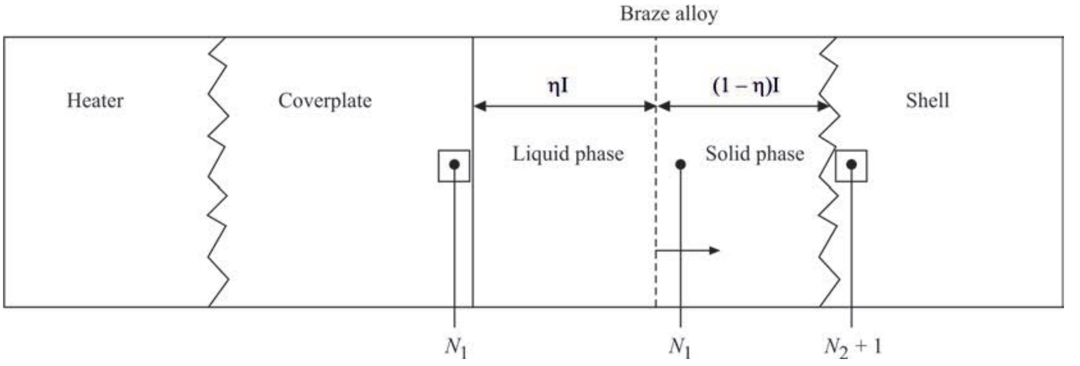

Figure 4. Schematic image of the position of the interface between the liquid and solid phase of braze alloy at its partial melting η

Change of the position of the boundary of braze alloy melt during time dt can be calculated from equation

$$\eta_i^{\text{new}} = \eta_i + \frac{dt}{\rho_{\text{br}}\lambda_{\text{br}}L}\times$$
$$\times\left(\frac{2\kappa_1^{\text{s}}\kappa_1^{\text{l}}}{2\kappa_1^{\text{s}}\eta L + \kappa_1^{\text{l}}dx}(T_{N_1} - T_{evt}) + \mu_1(T_{N_2+1} - T_{evt})\right). \quad (14)$$

Change of temperature on the boundaries with the plates, allowing for partial melting or solidification of the braze alloy, can be calculated from the following expressions:

$$T_{N_1}^{\text{new}} = T_{N_1} + \frac{dt}{dx\rho_{\text{pl1}}c_{\text{pl1}}}\times$$
$$\times\left(-\frac{\kappa_1^{\text{s}}}{dx}(T_{N_1} - T_{N_1-1}) + \frac{2\kappa_1^{\text{s}}\kappa_1^{\text{l}}}{\kappa_1^{\text{s}}\eta L + \kappa_1^{\text{l}}dx}(T_{N_1+1} - T_{N_1})\right), \quad (15)$$

$$T_{N_2+1}^{\text{new}} = T_{N_2+1} + \frac{dt}{dx\rho_{\text{pl2}}c_{\text{pl2}}}\times$$
$$\times\left(\mu_1(T_{evt} - T_{N_2+1}) + \frac{\kappa_1^{\text{l}}}{dx}(T_{N_2+2} - T_{N_2+1})\right). \quad (16)$$

If the composition of the interlayer includes MF based on reactive elements, then during heating the diffusion processes between the reactive element layers will be initiated in the foil, leading to formation of intermetallic compounds. As this process will be accompanied by heat evolution, cells contacting the foil will be heated by heat flow not only from the heater, but also from MF.

Using Wagner coefficient of diffusion [12] and the law of phase growth at reaction diffusion [13], it is possible to determine the thickness of the interlayer of intermetallic phase, which forms on the boundary of reactive element layers, $d\Delta y$ during time interval dt, as

$$d\Delta y = \frac{D_0\Delta g}{k_B T_{N_1} c(1-c)}\exp\left(-\frac{Q}{k_B T_{N_1}}\right)dt,$$

where T_{N_1} is the temperature of the interlayer with a multilayer structure at the initial moment of time.

Change of temperature in the foil cell as a result of such a phase transformation is determined as

$$T_{N_1} = T_{N_1} + \frac{d\Delta y}{2l}\frac{\Delta g}{3k_B}.$$

where Δg is the heat of formation of the intermetallic phase during the reaction of synthesis in the multilayer structure with modulation period $2l$. Here, it is necessary to take into account the fact that the process of heat generation starts at the thickness of new phase interlayer $\Delta y = \Delta y0$ and goes on up to complete transformation of MF into intermetallics.

If the interlayer composition includes a layer of braze alloy, the calculation took into account absorption of thermal energy in this layer, which is consumed for its heating and melting.

Such a scheme of calculation of the thermal field in the system can be defined both as spatial distribution of temperature, and as its change in a specified point, depending on the time of local heating process.

Within this scheme, temperature distributions when producing permanent joints of aluminium plates by brazing or welding were studied under the condition that the zone of contact of heater with the coverplate and of the coverplate with the shell has contact points, and the coefficients of heat transfer between them are described by relationship (3).

Calculation results. Temperature variation in the interlayer, consisting of a layer of braze alloy during local heating of the joint zone is shown in Figure 5.

One can see that the heater thickness influences the features of temperature variation in the interlayer: at heater thickness below a certain critical value (at selected parameters of the system this corresponds to heater thickness of 5 mm), the temperature in the interlayer increases monotonically. It, however, does not reach braze alloy melting temperature, and at

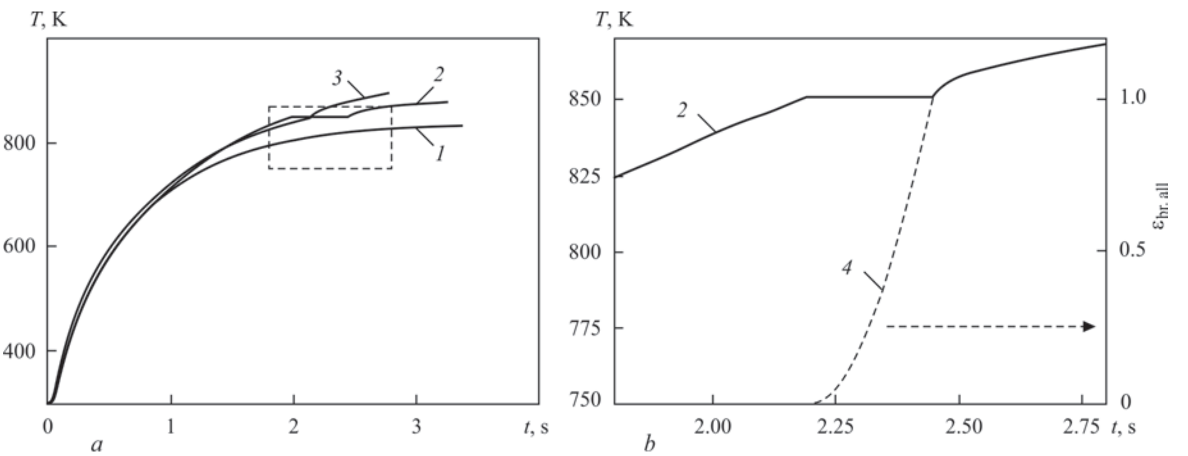

Figure 5. Temperature changes in 100 μm thick interlayer based on «eutectic alloy» (melting temperature of 850 K), depending on thickness of heater with adiabatic temperature of SHS reaction of 1600 K: *1* — d = 5; *2* — 6; *3* — 7 mm (*a*); the insert shows the dependence of melt volume fraction ε_{br} in braze alloy interlayer (curve *4*) during local heating of the joint zone for curve *2* (*b*)

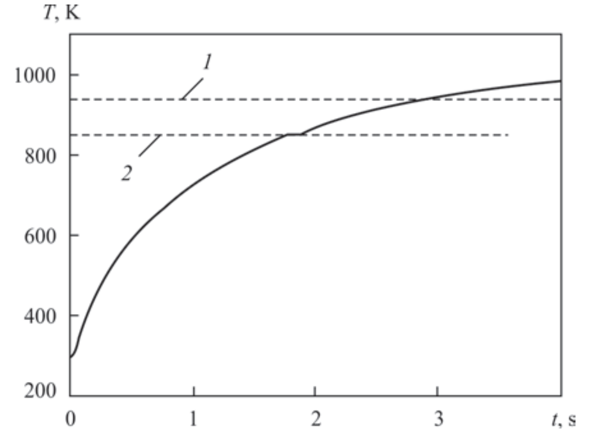

Figure 6. Change of temperature in 100 μm interlayer based on «eutectic alloy» (melting temperature of 850 K) at local heating of plates by 9 mm thick heater (heater adiabatic temperature of 1600 K): *1* — melting temperature of aluminium plates; *2* — braze alloy melting temperature

thickness greater than the critical one (6 mm) a section of slow temperature rise is observed on the temperature dependence. One can see in Figure 5 that this «site» on the temperature dependence corresponds to braze alloy melting. Volume fraction of molten braze alloy becomes larger during soaking at this temperature. Further temperature rise in the interlayer is observed only after complete melting of the braze alloy.

Proceeding from that, it can be assumed that to ensure the temperature mode of brazing the heater thickness should exceed a certain lower limit. However, if a thicker heater were to be used, for instance, 9 mm thick, the temperature in the contact zone after complete melting of the braze alloy will continue rising right up to melting temperature of the aluminium alloy (Figure 6). This results in partial melting of the coverplate, contacting the heater.

Thus, in order to ensure the conditions, required for brazing, the heater thickness should be between the lower and upper limits, that allows melting the braze alloy without leading to coverplate melting.

As the intensity of the heat flow propagating from the heater to the coverplate, depends not only on heater thickness, but also on adiabatic temperature, which it reaches as a result of SHS reaction passing in it, the values of the lower and upper limits of heater thickness were determined in the work, depending on its temperature in the range of 1300–1600 K. Here, the lower limit corresponds to the condition, at which braze alloy melting proceeds without surface melting of the coverplate layers, contacting the heater, and the upper limit corresponds to the conditions of partial (up to 10 %) melting of the coverplate.

One can see from Figure 7 that with increase of adiabatic temperature of the heater, the values of lower and upper limits of its thickness become smaller, as does the difference between these limits. At heater temperature above 1600 K, partial melting of the coverplate is observed already at thicknesses below the lower limit.

Based on that we can conclude that there exist certain limitations, not only for selection of heater thickness, but also for adiabatic temperature, which it reaches as a result of SHS reaction running in it.

Temperature distribution across the cross-section of the assembly at different stages of its heating is shown in Figure 8 for the case of application of the heater, satisfying the above requirements. One can see that for such heaters at all the stages of local heating of the joint zone, the temperature in the contact zone of the heater and coverplate remains practically unchanged, and its value is below the melting temperature of plate material (AMg6 alloy).

A qualitatively new kind of temperature variation is observed in the case, when the interlayer consists of MF based on reactive elements. As one can see from Figure 9, at heating of such an interlayer the nature of its temperature variation depends on heater thickness. A heater thickness of the order of 1 mm, interlayer heating proceeds monotonically. At increase of

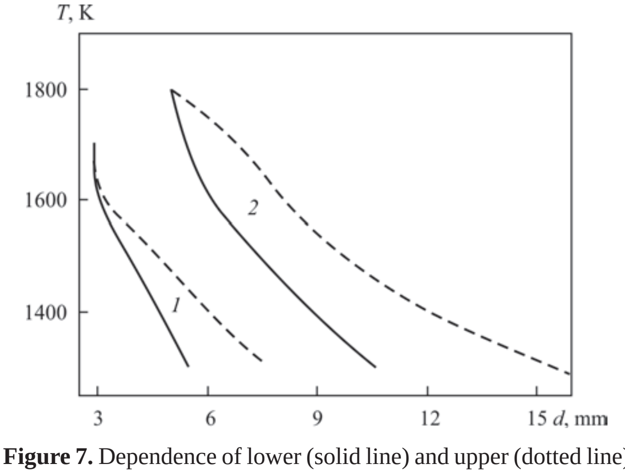

Figure 7. Dependence of lower (solid line) and upper (dotted line) values of heater thickness limits on its adiabatic temperature: *1* — optimum thickness of heater for joining 5 mm aluminium plates; *2* — 10 mm

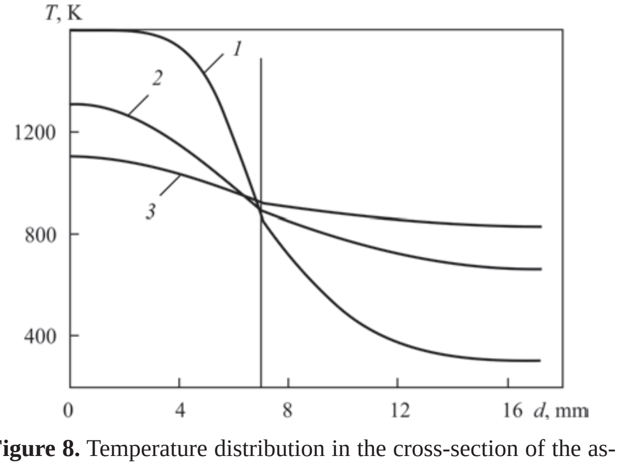

Figure 8. Temperature distribution in the cross-section of the assembly, consisting of 7 mm thick heater, 5 mm coverplate; 100 μm interlayer and 5 mm second plate at different stages of the brazing process: *1* — 0.1 of the process; *2* — 1; *3* — 1.9 s

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heater thickness an abrupt increase of temperature is observed on temperature dependence, which after reaching a certain peak value decreases to the level of monotonic dependence, similar to the one characteristic for local heating of the plates in the case of application of interlayers based on braze alloy.

According to work [14], such an abrupt temperature rise in the interlayer with a multilayer structure based on reactive elements can be related to initiation of thermal explosion reaction (TE) in the foil, at which the process of high-temperature synthesis runs in its entire volume without any additional heat input. There exists a threshold value of MF heating temperature for TE initiation: at MF heating rates below the threshold value, the synthesis reaction develops in the mode of solid-phase reaction, requiring continuous heat input, and at higher heating rates the heat generated through high-temperature synthesis, ensures running of this reaction without any external heat input. Therefore, at low heating rates, which are realized in the case of application of 1 mm thick heater, TE is not initiated, whereas at increase of the heating rate due to the heater 1.5 mm thick TE is initiated, which is accompanied by an abrupt increase of temperature in the joint zone. At further increase of MF heating rate due to increase of heater thickness, the value of temperature peak increases, whereas the time of its initiation shifts closer to the start of the heating process.

Ability to heat the joint zone of aluminium plates due to the heat, released in MF at TE, was studied from the viewpoint of creation of thermal conditions for surface melting of aluminium layers, contacting MF that is a mandatory condition for fusion welding. Figure 10 shows temperature distribution in the assembly cross-section at the moment of initiation of synthesis reaction in TE mode in MF. One can see that with increase of MF thickness the temperature in the joint zone rises at TE initiation. Here, a considerable temperature rise is observed in the interlayer and sections of the joined plates contacting MF. At more than 200 μm thickness of the interlayer, the temperature of aluminium alloy layers contacting MF, becomes higher than its melting temperature. It can be assumed that such temperature conditions on the boundary of MF and aluminium plate can promote melting of its surface layers.

Therefore, at application of MF as interlayer, additional heating of aluminium plate layers contacting MF can be provided, as a result of initiation of synthesis reaction in TE mode in it. Owing to increase of MF layer thickness, the quantity of heat generated here, can provide surface melting of aluminium plates, required for their welding.

Note that for the welding mode the heater thickness can be significantly smaller than in the case of

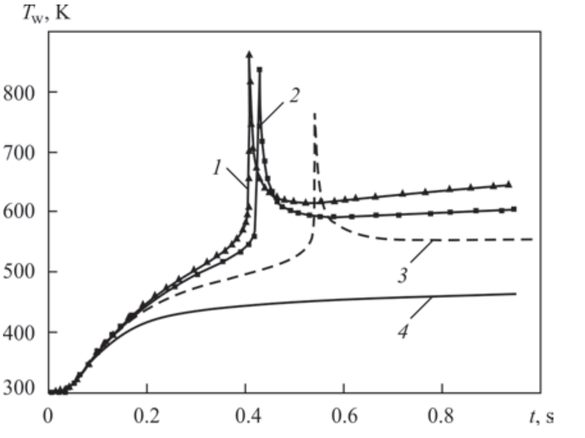

Figure 9. Changes of temperature in the interlayer from MF based on Ni/Al (200 μm thickness with 100 nm period), depending on the time of reaction running at different heater thicknesses: *1* — *d* = 2.5; 2 — 2; *3* — 1.5; *4* — 1 mm, heated up to the temperature of 1600 K

joining plates in the brazing mode. Proceeding from that the possibility of TE application to ensure the thermal conditions required for brazing in the case of application of layers of braze alloy and MF as interlayer, was considered.

Figure 11 shows temperature distribution in the cross-section of an assembly, consisting of a layer of MF and layer based on braze alloy, at the moment of TE initiation. One can see that as a result of TE, the temperature in the interlayer increases abruptly up to values, exceeding the braze alloy melting temperature. Proceeding from that, it can be assumed that such an interlayer structure allows reducing the heater thickness, compared with the process of brazing through the interlayer based on braze alloy, and, consequently, lowering the temperature to which the assembly as a whole will be heated.

The above parameters, characterizing the heater, and their connection with interlayer parameters and thickness of the joined plates, were obtained for the

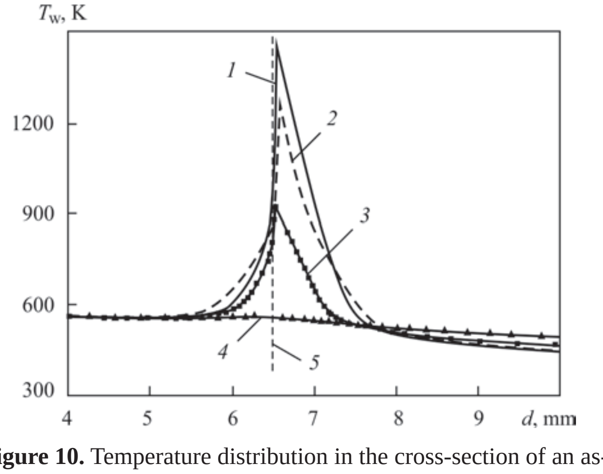

Figure 10. Temperature distribution in the cross-section of an assembly, consisting of heater, coverplate, interlayer based on MF and shell, at the moment of TE initiation in it (heater thickness of 1.5 mm) with different MF thickness: *1* — *df* = 350; *2* — 300; *3* — 200; *4* — 100 μm; *5* — zone between coverplate and MF

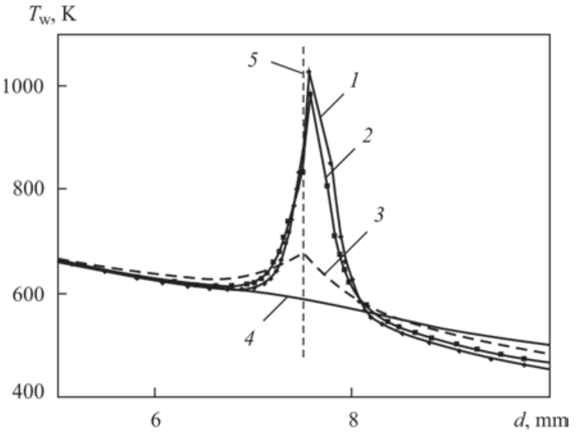

Figure 11. Temperature distribution in the cross-section of an assembly, consisting of heater, coverplate, interlayer based on MF, braze alloy layer (100 μm thickness of braze alloy) and shell, at the moment of TE initiation in MF (heater thickness of 2.5 mm) at different MF thickness: *1* — *df* = 200; *2* — 150; *3* — 100; *4* — 50 μm; *5* — zone between coverplate and MF

case of joining 5 mm thick plates. To clarify the applicability of this approach for joining thicker plates, the temperature fields were calculated in the work, which are required for realization of such a joining scheme. It turned out that the main regularities of local heating of the joint zone using the heater, contacting the coverplate, are preserved under the condition of increasing the heater thickness in proportion to increase of the thickness of the plates being joined, right up to 20 mm.

Conclusions

1. It is shown that at local heating of the zone of the joint of aluminium alloy plates from AMg6 alloy up to 20 mm thick, by a heater based on MF, contacting one of them (coverplate), temperature conditions can be provided, which are required for melting the braze alloy located in the joint zone without melting the aluminium plate.

2. To ensure the temperature conditions, required for the process of brazing the aluminium plates through an interlayer based on braze alloy, at local heating of the joint zone by a heater contacting one of the plates, its thickness should be greater than a certain critical value, dependent on adiabatic temperature of the heater, characteristics of the interlayer based on the braze alloy and plate thickness.

3. It is shown that there exists an upper limit of adiabatic temperature of the heater, above which melting of the coverplate material can occur earlier, than melting of the braze alloy layer, located in the joint zone.

4. Application of multilayer foil as interlayer, for instance, Ni/Al, which is highly reactive, can ensure the temperature conditions for running of the welding process due to local melting of aluminium alloy layers contacting the interlayer, as a result of initiation of synthesis reaction in the foil by the scheme of thermal explosion (bulk synthesis reaction) at local heating of the joint zone by the heater, contacting the coverplate.

5. Application of an interlayer from highly reactive multilayer foil, for instance, Ni/Al, in combination with a layer of braze alloy, allows reducing the thickness of the heater, required to provide the temperature conditions for the brazing process due to additional heat generation in MF at initiation of high-temperature synthesis in it in thermal explosion mode.

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