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INFLUENCE OF THERMAL CONTACTS ON HEATING ALUMINIUM PLATES UNDER NON-STATIONARY HEATING CONDITIONS, USING THE SHS-PROCESS

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ABSTRACT

The temperature of the heater, which can be used to join a plate of limited dimensions, to a shell of unlimited dimensions by brazing, in the general case is determined by melting temperature of the filler metal and characteristics of heat transfer in the plate contact zone. In the case of a low heat transfer in the contact zone, its heating to the temperature required for brazing is complicated, as a result of spreading of the heat coming into the shell. The work is an experimental study of the impact of imperfect thermal contacts between the aluminium plates on their heating, using a flat heater, which is in contact with one of the plates. It turned out that the force of pressing the contacting plates to each other has a greater effect on heat transfer in the contact zone than the surface roughness. Here, the value of the coefficient of effective heat transfer changes jumplike during heating of the plates, which is associated with microplastic deformation of their surface layers under the impact of a compressive load. A computational-experimental method of self-consistent determination of the values of the coefficient of effective heat transfer for different temperatures was proposed, which is based on comparison of experimentally measured and calculated thermograms of plate heating.

KEYWORDS: temperature fields, non-stationary heating process, thermal contacts, brazing, multilayer foils

INTRODUCTION

Repair of large-sized shell structures can be performed by applying a patch which is joined during brazing using local heating of the joint zone by a flat heater which is in contact with the coverplate (Figure 1). It is assumed that the heater parameters (temperature, weight, etc.) should ensure filler metal melting in the plate joining zone without surface melting of the coverplate which is in contact with it [1].

The respective brazing scheme under the conditions of stationary heating of the joining zone by a heater with constant temperature was analyzed in works [2, 3] for piping repair in space. When solving this problem, it was assumed that thermal contacts between elements of the system, consisting of a pipe, coverplate, filler metal and heater, are ideal. It is shown that such a brazing scheme can ensure local heating of the joining zone up to the temperature of filler metal melting, provided that the heater temperature exceeds a certain limit quantity, the actual value of which depends on the weight and dimensional parameters of the assembly. Application of such a brazing scheme, however, envisages use of high-capacity power sources to prevent heat spreading through the pipe during heating.

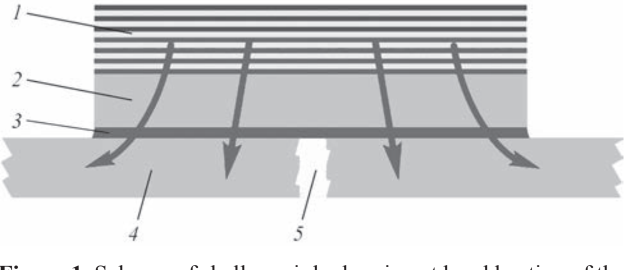

Figure 1. Scheme of shell repair by brazing at local heating of the joining zone by a flat heater (under non-stationary conditions): *1* — heater; *2* — coverplate; *3* — filler metal; *4* — shell; *5* — hole (arrows show thermal energy propagation (conditionally))

High-capacity heat sources used for brazing can be replaced by a chemical heat source based on multilayer foil (MF), which consists of highly-reactive elements, such as nickel and aluminium. At initiation of the reaction of self-propagating high-temperature synthesis (SHS) in such a foil, formation of the intermetallic compound is accompanied by intensive heat evolution, which ensures the heater heating to adiabatic temperature of SHS reaction in a short period of time. In case of application of multilayer Ni/Al foils the heater can reach the temperature of ~1800 K in fractions of a second [4].

The heater power is obviously proportional to the weight of the reaction material in multilayer foil, as well as its thickness. Changing MF weight (or thickness) in the heater allows ensuring the required temperature conditions for brazing on the surface of a shell of unlimited dimensions. It was found [1] that in the approximation of ideal thermal contacts there is the optimal MF thickness for realization of the brazing process. In our case, when it is necessary to ensure high power, and the heater is assembled not from one, but from several foils, thickness control becomes a problem, and it is better to proceed exactly from the total weight of the reaction material. At heater weight below the optimal one, the filler metal melting temperature is not achieved in the joining zone. If the heater weight is greater than the optimal one, surface melting of the coverplate, which is in contact with it, can occur.

As the temperature in the joining zone is determined by the balance of heat fluxes from the heater into the coverplate and from it into the shell through the filler metal, the filler metal temperature and its melting time, in their turn, will be determined not only by thermophysical characteristics of the materials of system elements (heater, plates and filler metal), but also by the characteristics of thermal contacts between them. Unlike the material thermophysical characteristics, those of the thermal contacts are unknown a priori, and they can change in a broad range, depending on a number of factors. It is known that the resistance to propagation of the heat flux in the contact between the two flat plates, pressed to each other, is due mainly to imperfect fit of their surfaces [5, 6]. Heat exchange between the plates in vacuum at a relatively low temperature in the contact zone (below 1000 K), when heat transfer through radiation and convection can be ignored, will be chiefly determined by the area of the surface of physical contact of the plates, which depends on their surface relief.

At pressing of the plates in the points of contact, in which the load is higher than the material yield limit, a local plastic deformation of the protrusions will take place, leading to increase of the area of the plate physical contact, and, hence, to reduction of the resistance to heat flux propagation.

Thus, heat conductivity in the contact zone depends not only on contacting surfaces roughness, but also on the force of their pressing together and mechanical properties of the contacting materials. Moreover, as the material yield limit in the general case depends on temperature, a change in the thermal contact characteristics at heating is to be anticipated, even at a constant compressive force.

In the work, the change of temperature in the plates during their non-stationary heating, depending on surface roughness and the force of their pressing together, was studied, in the case of a model system, which consists of a flat heater, contacting AMg6 plates.

EXPERIMENTAL PROCEDURE

The scheme of temperature measurement in AMg6 plates during heating is shown in Figure 2.

Plates from AMg6 aluminium alloy of 50×50×5 mm size were cut out of a sheet. After that their contact surfaces were ground to ensure thermal contact over the entire plane. They were placed into a clamping device one above the other. Installed above the upper plate was a heater — a Ni/Al MF packet, which is in contact with it over the entire plane. In order to study the influence of roughness on heat transfer in the contact zone, plates were prepared, the contact surfaces of which were pre-treated with sand paper to achieve roughness indices of 0.3 and 2.5 μm, which were determined by the used paper grit. Pressing down of this assembly was provided by a spring, which was placed above the heater, and was compressed to the specified loading value, proceeding from the readings of the strain gauge, mounted under the lower plate.

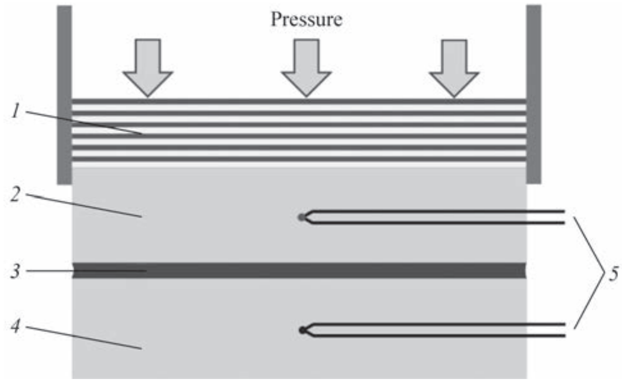

Figure 2. Scheme of the assembly used for experimental study of temperature fields during brazing of AMg6 aluminium plates (*2*, *4*) separated by filler metal interlayer (*3*), at heating with a heater from multilayer foils (*1*), which is in contact with the coverplate (*2*); *5* — thermocouples inserted into plates

To model the plate joining by brazing, a layer of Al–Si filler metal 100 μm thick was deposited by EB PVD method on the surface of the upper coverplate, which is in contact with the lower shell-plate. SHS reaction in Al/Ni MF was initiated by feeding a current pulse from a pre-charged capacitor to the nichrome spiral, which locally heated the MF in the contact area. The high velocity of SHS reaction propagation in MF (1–2 m/s) ensured fast heating of the heater to adiabatic temperature of the reaction of NiAl intermetallic synthesis. Change in the plate temperature with time was measured using KhA thermocouples with 0.15 mm wire diameter. Thermocouples in ceramic insulation were inserted into 2.5 mm diameter channels drilled in the plates so that their junctions were in the center of the plates, pressed against them. It was assumed that thermocouple inertia can be neglected for these processes. Thermocouple readings were recorded on the computer by a controller with recording frequency of 1 kHz. To reduce heat losses and convective heat exchange between the system elements, the assembly was placed into a vacuum chamber (residual pressure of ~ 0.1 Pa).

PROCEDURE OF NUMERICAL MODELING OF TEMPERATURE FIELDS

Numerical modeling of temperature fields was performed in the assumption that all the system elements (heater, AMg6 plates) have unlimited dimensions in the plate joining plane and limited dimension in the normal direction. In this case, the problem is reduced to analysis of heat redistribution in one direction, normal to the contact plane. Accordingly, all the elements were divided into layers of final thickness Δx. It was assumed that there is no thermal energy radiation outside the system, and, thus, boundary conditions of the second kind will be satisfied for extreme layers (0-th and N_{max}): $T_0 = T_1$, $T_{N_{max}} = T_{N_{max}-1}$, where N_{max} is the maximal layer number: $N_{max} = \frac{L_0}{\Delta x} + \frac{L_1}{\Delta x} + \frac{L_2}{\Delta x} + 2$, where L_0 is the heater thickness; L_1 is the coverplate thickness; L_2 is the shell thickness. The interlayer based on the filler metal was considered as one layer.

In order to determine the temperature in each layer, it is necessary to solve the equation of heat conductivity, allowing for the thermophysical properties of the layer materials:

$$\frac{\partial T}{\partial t} = a\frac{\partial^2 T}{\partial x^2}, \quad (1)$$

where a is the thermal diffusivity coefficient (m^2/s) for the layer material.

Equation (1) has a solution for all the system layers of width Δx:

$$T_i = T_i^{\text{old}} + a_i \frac{T_{i+1}^{\text{old}} - 2T_i^{\text{old}} + T_{i-1}^{\text{old}}}{\Delta x^2} dt, \quad (2)$$

where T_i^{old} is the initial temperature of the i-th layer, and T_i is its temperature after time of dt seconds.

This relationship is valid for all the layers, except those, which belong to different system elements. In order to calculate the boundary layer temperature, it was taken that the heat flux is proportional to temperature difference in boundary layers i and i+1, heat transfer between which is characterized by "effective heat transfer coefficient" $\mu_{i,\,i+1}$ in keeping with the following relationship

$$J_{i,i+1} = \mu_{i,i+1}\left(T_{i+1} - T_i\right), \quad (3)$$

where $J_{i,\,i+1}$ is the heat flux between i and i+1 layers, the temperatures of which are T_i, and T_{i+1}, respectively.

In the case of an ideal thermal contact between i and i+1 layers, belonging to different system elements with heat conductivity coefficients of their materials k_i, k_{i+1} and thicknesses h_i and h_{i+1}, respectively, the effective heat transfer coefficient was determined as

$$\mu_{i,i+1} = \frac{2k_i k_{i+1}}{k_i h_{i+1} + k_{i+1} h_i}. \quad (4)$$

Therefore, the temperatures of the adjacent layers were determined using systems of equations, including equations of types (2) and (3) for heat fluxes between the boundary and adjacent to them layers [7], and heat transfer coefficients were assigned a priori for imperfect contacts, or they were calculated by formula (4) in the case of ideal contacts. Numerical realization of this algorithm allows calculation of temperature distribution by system thickness for any moment of time t or temperature change in the set point, depending on time. The start of timing was taken to be the moment of completion of SHS reaction in MF, when the heater temperature reaches the adiabatic temperature of high-temperature synthesis of NiAl intermetallic. Considering that the speed of SHS reaction front propagation is equal to ~1–2 m/s, the heat exchange between the heater and the plate was ignored. It was also considered that the thermophysical characteristics of system elements (thermal diffusivity and heat capacity of heater and plate materials) are independent of temperature. In the presence of filler metal between the plates, it was taken into account as a separate interlayer with its own thermophysical properties, which were determined according to its chemical composition. The peculiarities of taking into account the layer of filler metal between the plates are described in detail in [8].

INVESTIGATIONS RESULTS AND THEIR DISCUSSION

Figure 3, *a* shows the thermograms of temperature change in plates with different roughness. Compression in the joining zone was equal to 60 kPa. One can see that the coverplate temperature abruptly and non-monotonically rises after initiation of SHS reaction in MF. Although the heater quickly reaches the temperature of 1700 K and higher, no surface melting of the plates which are in contact with it was observed. This is the result of high heat conductivity of aluminium alloys, due to which the thermal energy is removed so quickly from the contact zone that no local overheating above the melting temperature occurs in it. Such melting can be observed only at considerable overheating of the assembly, when the melting temperature is reached for the plate as a whole, and not only in the contact zone. Heating of the other plate ("shell") occurs with a certain delay, the "lag" in temperature rise in it becoming greater with greater roughness of the plate contact surfaces. It is obvious that such a lag is due to poorer heat exchange in the plate contact zone as a result of reduction of the effective thermal contact area.

Pressure increase at unchanged roughness of plate contact surfaces (Figure 3, *b*) leads to lowering of coverplate heating rate and increase of shell heating rate, i.e. to reduction of temperature difference between the coverplate and the shell at each moment of time, which is indicative of higher heat exchange in the contact between them. Note that the nature of the coverplate temperature change becomes qualitatively different with increase of pressing force: at smaller pressing force its temperature first increases abrupt-

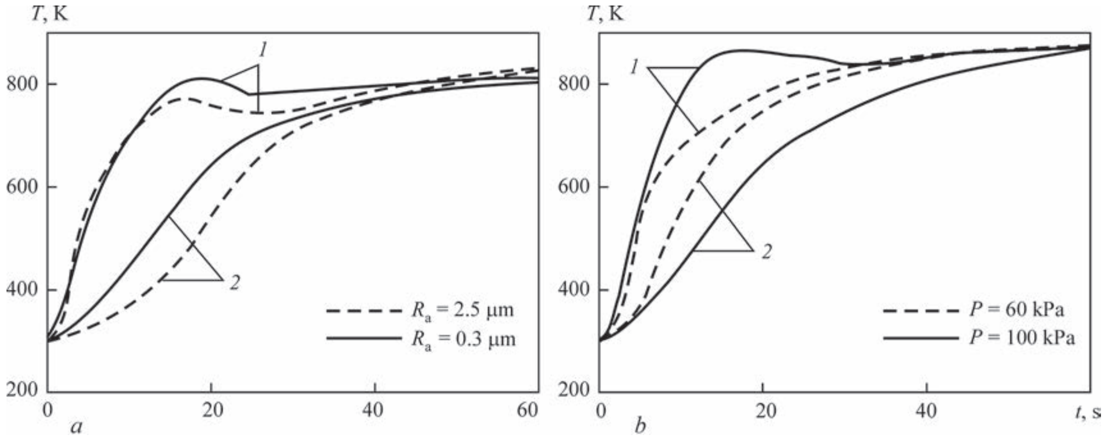

Figure 3. Influence of plate surface roughness at constant pressure of 60 kPa (*a*) and at constant roughness R_a = 0.3 μm (*b*) on temperature change during their heating: *1* — coverplate; *2* — "shell"-plate

ly and then somewhat decreases; at greater force the change in its temperature is of a more monotonic nature. Some, relatively minor differences in the shape of the curves for P = 60 kPa, R_a = 0.3 μm are related to errors of heater dosing and deviations of the foil chemical composition from the average value.

As the non-monotonic shape of the thermogram of upper plate heating is observed under the condition of weaker heat transfer in the contact between the plates, we assumed that at the initial moment of heating the applied pressure is insufficient to achieve the best contact between the plates. When the plate temperature rises, at the same pressure, microplastic deformation of their surface layers is achieved, which improves the contact surfaces fit, and, hence, also the heat exchange.

Comparing the time dependencies of system element temperature one can see (Figure 3, *b*) that the bends on the coverplate and shell thermograms, which point to a decrease of the heating rate of the first and increase of the heating rate of the second, coincide in time, which is an indication of improvement of thermal contact between the plates at this moment. Proceeding from the obtained experimental results, we came to the conclusion that at heating of AMg6 plates by MF, which is in contact with the coverplate, with superposition of constant pressing in the range of 60–100 kPa, conditions are in place, which are necessary for material plastic deformation in the contact zone.

In order to test this assumption, experiments were conducted on heating AMg6 plates, separated by tungsten threads 0.3 mm thick to simulate "poor thermal contact" in the butt at the start of heating (Figure 4, *a*). Obtained experimental thermograms are given in Figure 4, *b*. One can see that first the coverplate is heated at a high rate up to a certain moment of time. After that its temperature rise slows down and even its slight lowering occurs. At the same moment of time, a bend is observed on the shell-plate thermogram, which indicates an increase of its heating rate.

Examination of plate surfaces after completion of the thermal cycle showed (Figure 5) the presence on them of imprints from thin tungsten threads, which separated these surfaces before the start of heating. These imprints were not observed under the conditions of compression of a similar assembly with the same force, but without heating.

Appearance of imprints indicates that at plate heating at a constant load the conditions of plate material plastic deformation are achieved due to lowering of its yield limit with temperature rise. Indeed, investi-

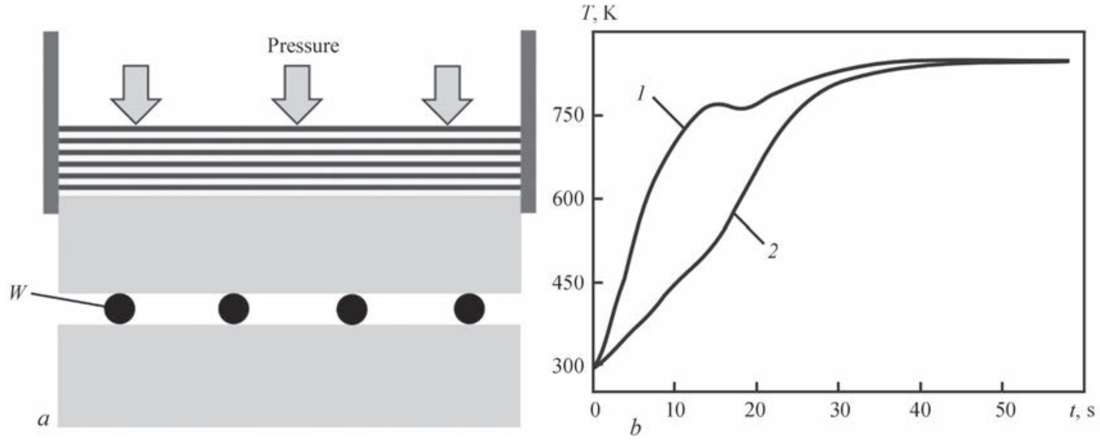

Figure 4. Scheme of heating of plates (*a*), separated by tungsten threads (W) and experimental thermogram of heating of coverplate (*1*) and "shell" (*2*) plates separated by thin tungsten threads at constant pressure of 100 kPa (*b*)

Figure 5. Surfaces of AMg6 alloy plates after thermal cycle of heating under the conditions of their compression with 100 kPa force

gations of the dependence of yield limit on temperature in aluminium alloys in works [9, 10] showed that the yield limit can decrease several times at heating, compared to this value at room temperature.

Thus, the heat transfer parameters in the zone of plate contact at their heating under constant loading can change, as a result of achievement of the conditions of plastic deformation of plate material at their heating. It leads to an essential decrease of the heating rate of the coverplate, which is in contact with the heater, and increase of the shell heating rate. In some cases, increase of the heat transfer coefficient on the boundary of the two plates during their heating may lead to appearance of a "shelf" on the coverplate thermogram, similar to the one observed at material melting. This effect is, probably, due to transition from elastic deformation of material of the plate surface layers to their plastic yield under the impact of the applied pressure at the temperature, at which the plate material yield limit decreases to the level corresponding to the pressing force.

It is clear that if the contacting surface material has a lower yield limit, than does the AMg6 alloy, the temperature of such a transition will be even lower. To test this assumption, investigation of AMg6 plate heating was conducted, when one of the contact surfaces of the coverplate was coated by multilayer filler metal based on AlSi. It turned out (Figure 6) that the temperature of the change in the slope of the curves in the thermograms is lower than at heating of the plates without the filler metal. Peak values of temperature turned out to be lower than in the previous experiments (Figure 3, *a*, *b*), which is related to errors in heater mass dosing. Considering that melting temperature of AlSi filler metal is equal to ~850 K, when the temperature of multilayer foil of a eutectic composition becomes close to this temperature, it undergoes structural changes, affecting mainly, the filler metal mechanical behaviour, namely its deformational behaviour under the pressing force. It results in the yield limit of multilayer filler metal decreasing at heating, which may have an essential influence on the characteristics of thermal contact between the plates [11].

MATHEMATICAL MODELING OF TEMPERATURE FIELDS

Mathematical modeling of the temperature fields was performed with variation of the coefficients of effective heat transfer in the contacts between the heater and coverplate ($\mu_{h,pl}$) and between the plates ($\mu_{pl,pl}$). Dependence (Figure 6, *a*, theor. 1) was obtained in the assumption that during heating the coefficients of heat transfer in the contacts remain constant ($\mu_{pl,pl}$ = $= 1\cdot10^5$ W/(m^2·K); $\mu_{h,pl} = 1\cdot10^4$ W/(m^2·K)), and dependence (Figure 6, *b*, theor. 2) — in the assumption that the coefficient of heat transfer in the plate contact zone at the temperature of 700 K rises from $\mu_{pl,pl} = 5\cdot10^4$ to $6.6\cdot10^5$ W/(m^2·K) at a constant value of the coefficient of effective heat transfer in the zone of contact of the heater and coverplate ($\mu_{pl,pl} = 9\cdot10^3$ W/(m^2·K).

It turned out that the calculated temperature changes at plate heating, provided that the heat transfer coefficients remain constant (Figure 6, *a*, curve theor. 1), are in good agreement at the initial stages only with experimental thermograms, obtained for a plate, which is in contact with the heater. At later stages of this process, a significant discrepancy between calculation and experiment is observed.

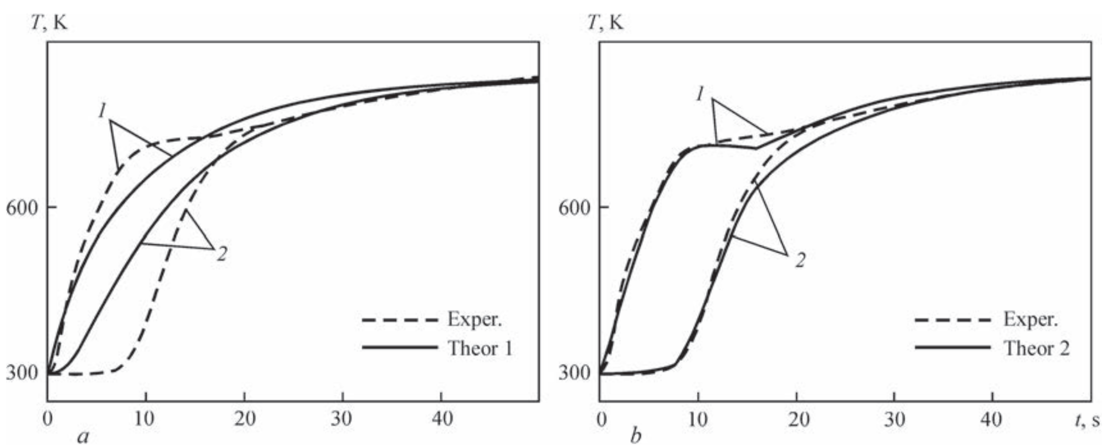

Figure 6. Temperature dependence in an assembly of AMg6 plates, separated by a filler metal interlayer, beginning from the time from the moment of SHS reaction passing in the heater under the conditions of 100 kPa constant pressure for coverplate (*1*) and "shell"-plate (*2*). Dashed lines are the results of experimental measurements; solid lines are the results of modeling at constant (*a*) and variable (*b*) coefficients of effective heat transfer

Modeling of the assembly heating process under the condition that a change in the coefficient of heat transfer in the contact between the plates occurs at achievement of a certain temperature of the coverplate (700 K), provided a much better agreement of the calculated and experimental thermograms (Figure 6, *b*, curve theor. 2).

Therefore, in order to predict the conditions of filler metal melting in an "open" system (joining a coverplate to a large-sized shell) using a heater with a set amount of heat, it is necessary to know not only the thermophysical parameters of materials (heat capacity, thermal conductivity, etc.) and thicknesses of system elements, but also heat transfer coefficients in the contacts between them. Obtained results show that these coefficients are not constant at temperature change, which essentially complicates assessment of heater parameters. Application of experimental thermograms and capabilities of numerical modeling of heating of plates of limited dimensions ("laboratory conditions"), allow determination of heat transfer coefficients in the contacts and the temperature of their change (which corresponds to the yield limit of plate material or filler metal at a certain load) by variation of these parameters to ensure the best agreement of the experimental and calculated values of plate temperature during their heating. Parameters of thermal contact derived during such a self-consistent calculation, can be used in further modeling of the process of heating of the joining zone on the surface of a shell of "unlimited" dimensions (under the conditions of the same roughness of the contacting surfaces and their pressing force), in order to determine the heating parameters ensuring the temperature conditions required for brazing.

CONCLUSIONS

It was found that the effectiveness of heat transfer in the zone of contact of AMg6 plates during their heating by a flat heater, which is in contact with one of them, depends both on the roughness of contacting surfaces, and on the pressing force. The heat exchange effectiveness becomes higher at reduction of the contacting surface roughness in the range from 2.5 to 0.3 μm and at pressure increase from 60 to 100 kPa. Improvement of heat exchange parameters at pressure increase during plate heating is associated with microplastic deformation of the plate surface layers, leading to increase of the area of their physical contact.

It is shown that comparison of plate heating thermograms obtained experimentally and calculated by numerical modeling allows determination of the coefficients of effective heat transfer in the zones of contact of the heater and coverplate and of the plates, as well as the temperature (temperature range) of transition from imperfect contact between AMg6 plates to their ideal contact under the conditions of non-stationary heating of the system at constantly applied pressure.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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