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FEATURES OF RESISTANCE PREHEATING IN FLASH-BUTT WELDING OF THICK-WALLED PARTS FROM ALUMINIUM ALLOYS

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ABSTRACT

The technological concept of flash-butt welding with resistance preheating using a reusable intermediate insert of a material with a high electrical resistance is proposed and substantiated by calculation. Calculation and experimental results indicate a significant effect of using intermediate insert during resistance heating: the temperature at both characteristic spots grows significantly at all investigated values of current density, insert thickness and heating time. The specified effect is achieved by intensifying and localizing the process of heat generation in the contact area of parts and correspondingly by reducing the energy loss for heating the secondary circuit of the welding machine.

KEYWORDS: flash-butt welding, resistance heating, aluminium alloy, mathematical modeling, temperature field

INTRODUCTION

An effective technology for producing permanent joint in the manufacture of load-carrying elements of aircrafts from rectilinear (stringers) and circumferential (shells) billets, pressed profiles of a developed and a compact cross-section (frame rings) is flash-butt welding (FBW). This method provides a high stable quality of joints, combines assembly and welding operations in a single cycle and does not require the use of auxiliary consumables [1–3]. In welding billets of aluminium alloys of up to 12 mm thickness, FBW technology provides high indices of strength and a high-quality (defect-free) joining at a slight width of the heat-affected zone (HAZ).

In FBW of profiles from aluminium alloys of larger thickness it is necessary to carry out a resistance preheating of billets by passing high-density electric current with a subsequent moving of billets apart and performing flashing and upsetting.

FBW technology with resistance preheating is widely used in various industries, in particular for joining parts of different thickness and configuration of steels of different classes [4–7]. In FBW of railway rails, preheating by current pulses [4, 5] (Figure 1, *a*) is used to provide the heat removal from the ends deep into billets. For more efficient resistance heating of billets from aluminium alloys, which have high values of electrical and thermal conductivity, continuous passing of current is used [1–3] (Figure 1, *b*).

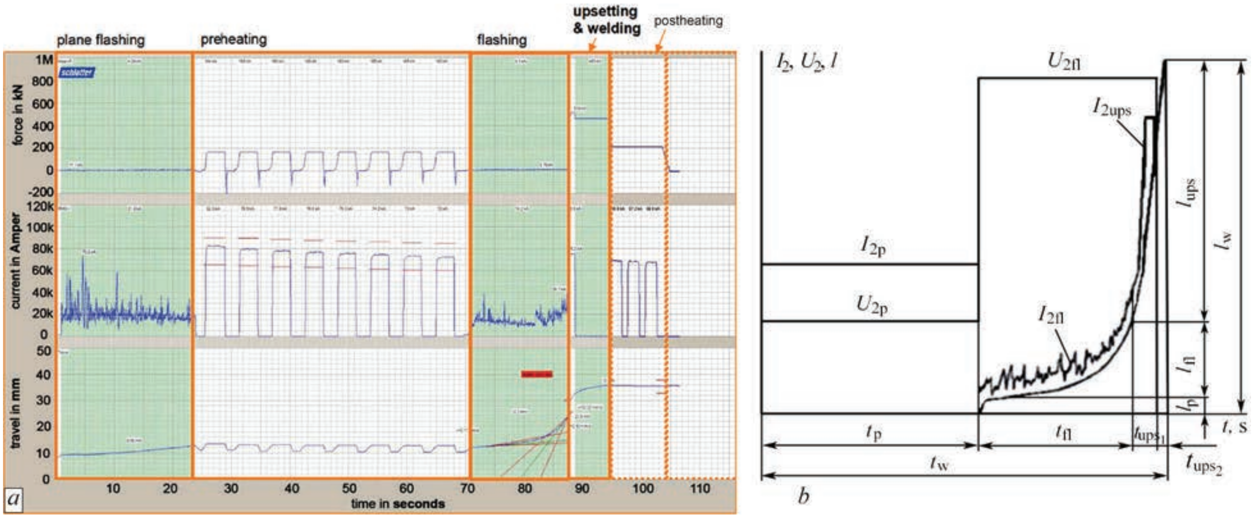

Figure 1. Cyclograms of the FBW process with preheating by current pulses (*a*) [5] and continuous (*b*) current passing [2]

Such heating process has low energy indices, and its duration reaches 80 % of the total welding duration [1]. Moreover, to ensure the formation of defect-free joints with an increase in the thickness of welded billets, the required resistance preheating temperatures grow. In particular, in [2] it is shown that in FBW of 2219 alloy, the optimal conditions of deformation during upsetting are provided during heating of the contact zone at the intensive deformation area to a temperature of about 400 °C. The need in increasing the resistance preheating temperature causes additional energy consumption for heating of the secondary circuit of the welding machine. At this time, the duration of the resistance heating stage grows, which leads to an increase in the width of welded joints HAZ and negatively affects the mechanical and operational properties of welded products from aluminium alloys.

Increasing the efficiency of resistance preheating, reducing its duration and loss of energy for heating of the secondary circuit of the welding machine is an urgent problem, the solution of which will provide significant energy saving and an improvement in the mechanical properties of welded joints of products of high-strength aluminium alloys.

The known technical solutions, where in order to increase the efficiency of heating in FBW, an interlayer in the form of a composite insert is used, in particular in welding of steel fittings [8], as well as in the form of a nanolayered foil (NF), in particular, in welding of titanium aluminides in similar [9] and dissimilar [10] joints.

In [8] in FBW of steel fittings, an interlayer represented a fluxed composite insert of profiled sheet of low carbon steel, which allowed localizing the process of heat generation in the contact zone. It is shown that when the current passes through the joint with an insert, which has a higher specific resistance, its intense heating and melting occurs. At the same time, the localization of heat generation is provided as compared to the traditional way of resistance heating, which contributes to the formation of quality joints at a smaller HAZ width than in welding without using an interlayer.

The authors [9, 10] investigated the features of formation of similar and dissimilar joints of Ti–46Al–2Cr–2Nb alloy based on γ-TiAl titanium aluminide in FBW, in particular, using interlayers in the form of NF. The work indicates that the presence of NF in the contact zone contributes to the formation of a thin layer of liquid phase at the initial stage of the heating process, localization of the heat generation process, the activation of the surfaces of both alloys at a much smaller duration of the heating stage as compared to welding without using an interlayer.

In [8–10] an intermediate insert represented thin foils, which are melted in the welding process and mainly displaced from the contact zone during upsetting, but they can partially remain in welded joints, significantly affecting their mechanical properties.

Unlike the abovementioned schemes of using a disposable insert that remains in the joint, for resistance preheating in FBW, it was suggested to use a reusable insert from a material with high indices of melting point and ohmic resistance. The technological concept of FBW applying a reusable intermediate insert was proposed, which is somewhat similar to butt welding process of polymer materials with heated tool [11]. However, it is significantly different, since the heat generation occurs both in the insert as well as in the welded parts, and the process of the temperature field formation depends on electrical and thermal processes, taking into account their complex interaction.

The aim of the work is to find the possibility of increasing the efficiency of resistance preheating process in FBW of aluminium alloys by intensification and localization process of heat generation in the contact area of the billets using an intermediate insert from a material with a high ohmic resistance.

RESEARCH METHODS, PROCEDURE, MATERIALS, EQUIPMENT

In the work, calculation and experimental research methods were used, in particular, the thermal cycles were calculated and the temperature fields were determined in the contact area of the billets using mathematical modeling of the heating process and by the empirical method while conducting experiments in the laboratory conditions.

The experiments were performed in a modernized K607 machine for FBW with a converted welding circuit, where as a power source, a welding transformer with 75 kV·A power was used, located directly under the current-conducting clamps of the machine.

For conducting experimental welds, the specimens of 2219 aluminium alloy with a cross-section of 32×60 mm were used. An intermediate insert represented plates of austenitic steel 12Kh18N10T of 7 mm thickness. The temperature fields were experimentally investigated using a computerized temperature registration system based on 8-channel USB-module for thermocouples Advantech USB-4718 using the chromelle-alumel thermocouples with a diameter of 0.5 mm.

Figure 2 shows the program for changing FBW mode parameters, which provides a consecutive change of four main stages of heating before forming a welded joint during upsetting. Between I and II stages, moving of the welded parts apart and clamping of the intermediate insert between them is performed, and between II and III stages, respectively, moving of the parts apart and removing of the insert from the gap between them is performed.

The scheme of the intermediate insert arrangement between the welded parts offered in this work is shown in Figure 3. In such a scheme of heating, the amount of heat dQ generated in the parts during resistance heating over the period of time dt according to the law of Joule–Lenz, can be represented as

$$dQ = I_{\mathrm{w}}^{2}(R_{\mathrm{in}} + R_{\mathrm{p}} + 2R_{\mathrm{c}})dt, \qquad (1)$$

where I_{w} is the welding current; R_{in} is the electric current of the insert; R_{p} is the electrical resistance of the welded parts; R_{c} is the transitional contact resistance between the parts and the insert.

CALCULATION STUDY OF THE RESISTANCE HEATING PROCESS

In FBW with resistance preheating, it is essential to achieve a certain value of temperature in the intensive deformation zone. The optimal conditions for the welded joint formation during upsetting are created when the yield and tensile strength of the material of the billets in the deformation zone are equal [2]. In this case, producing of welded joints is provided with a minimum level of inner stresses with the absence of microcracks and other defects. In FBW with the forced formation, the width of the intensive deformation zone practically coincides with the value of the upsetting tolerance, so the optimal conditions for deformation of the billets from 2219 alloy are created at a temperature of about 400 °C [2].

To optimize the temperature field, during resistance preheating of the billets, it is essential to reach the set temperature at characteristic spots, namely: at the first one – at the ends of the billets (contact zone) and at the second one – at a distance of about 30 mm from the contact zone. This value, which was determined on the basis of a previous practical experience on FBW of thick-walled parts of aluminium alloys, corresponds to half of the set value of the total welding tolerance $l_{\mathrm{w}} = 60$ mm ($l_{\mathrm{w}}/2 = 30$ mm), i.e., the second characteristic spot after performing the processes of flashing and upsetting will be in the plane of the welded joint.

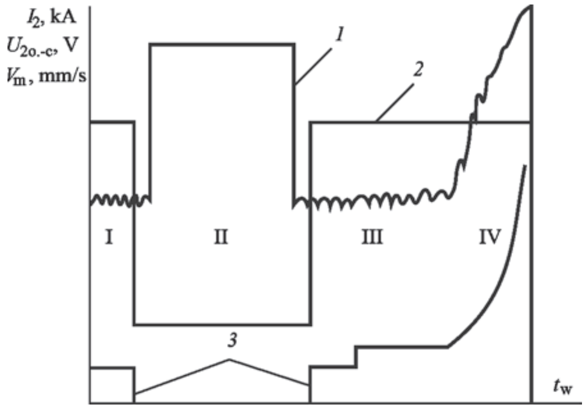

Figure 2. Program for changing parameters of FBW process with resistance preheating using an intermediate insert: I — preliminary flashing; II — resistance heating through an intermediate insert; III — flashing at a constant rate; IV — intensive flashing (forcing) before upsetting; *1* — welding current I_2; *2* — secondary open-circuit voltage of the welding transformer $U_{2\text{o.-c}}$; *3* — movement of the moving column of the welding machine V_{m}

As the criterion of efficiency of resistance heating, reaching a set temperature at the characteristic spots of parts at the least time at a set value of current density was considered. From the point of view of stability of flashing stages at a constant rate and intense flashing (see Figure 2, III and IV stages), the desired result of resistance preheating is the achievement of the highest possible value of temperature at the first of the characteristic spots (contact zone), but not lower than 150–200 °C [1, 12]. As the criterion of sufficient resistance heating of parts, reaching a temperature of 150 °C at the second of the characteristic spots (at a distance of 30 mm from the contact zone) was considered. In this case, in the process of the next stages of FBW, a gradual heating of the parts to a temperature of 400 °C is achieved in the deformation zone between the forming devices of the welding machine and the necessary conditions for the formation of defect-free welded joints are provided during upsetting.

The process of the temperature field formation in FBW is predetermined by the complex distribution of Joule heat sources. Heat transfer which, along with heat generation forms a temperature field in metal, is performed in a conductive way. The thermal conductivity of metal, its specific electrical resistance and other physical properties depend significantly on the temperature. The welding current, which determines the intensity of thermal impact on the metal depends on the open-circuit voltage, resistance of welded parts and inner resistance of the machine for resistance welding. Therefore, an adequate mathematical model of the process of the temperature field formation during resistance heating should include a description of electrical and thermal processes in the welded metal, taking into account their complex interaction. The welding current (current density) should be set on the basis of experimental data. The heat generation is determined by the calculation way, taking into account the electrical resistance of the welding zone, and the properties of the metal at each spot of the calculated

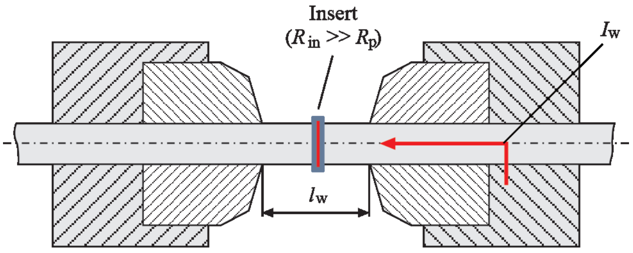

Figure 3. Scheme of the resistance heating process through an intermediate insert in the current-carrying clamps of the machine for FBW (l_{w} — tolerance for welding)

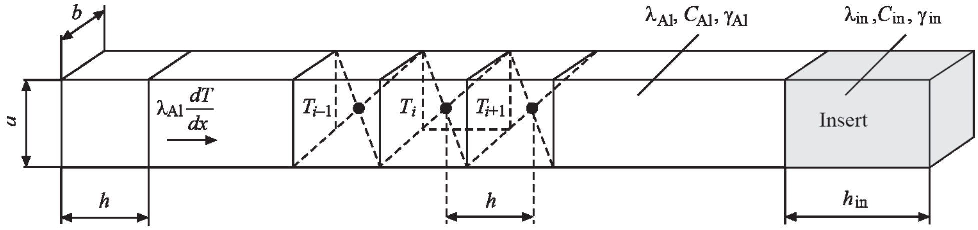

Figure 4. Scheme of the mesh of calculation model

area should be set according to the current distribution of the temperature filed of a part.

Unlike the predominantly volumetric heat generation in the billets between the current-carrying clamps of the welding machine during resistance heating without an insert (transient contact resistance between the parts from aluminium alloys is insignificant), during resistance heating through the insert, an additional source of heat generation appears, which can be linear (at a slight thickness of the insert, in particular, when using thin foil) or volumetric (when using a plate with a thickness of several millimeters). In the latter case, the temperature field in the heated parts will be formed according to a law close to the exponent.

The calculation scheme for the case of a one-dimensional problem is shown in Figure 4.

To simplify the calculation, the temperature distribution in the cross-section of the welded billets can be neglected. Based on this, the problem is solved in a one-dimensional statement. The one-dimensional nonstationary heat conduction equation for the case of a onedimensional problem in Cartesian coordinates has the following form [13]

$$c(T)\gamma(T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left[\lambda(T)\frac{\partial T}{\partial x}\right] + q_v, \tag{2}$$

where T is the temperature, K; t is the time, s; q_v is the volumetric density of inner heat sources, W/m^3.

Discretization of the calculation area was carried out, which consists in replacing the continuous determination area and the continuous area of the function value for the corresponding discrete areas. In our nonstationary problem, it is necessary to discretize both the spatial calculation area as well as the time. As the beginning of the countdown, let us choose one of the ends of the parts that is heated.

On the section of the axis x, let us select the spot x_i, $i = 0 - 1, \dots, n - 1, n$. Let us assume that the distance between two adjacent discretization spots x_i and x_{i+1}, equal to the discretization step h, will be the same, i.e., the discretization of the computational domain is uniform. At the same time, to each discretization spot x_i the value of the temperature t_i corresponds.

The welded specimen has a cross-section with dimensions $a \times b$. Therefore, the volume of one element is determined by the formula $a \times b \times h$. If the nonlinearity of the thermophysical properties of the heated parts is not previously taken into account (dependencies $\lambda(T)$, $c(T)$ and $\gamma(T)$), then the nonlinearity of the problem will consist only in taking into account the dependence of the power density of the Joule heat source q_s:

$$q_{\mathrm{J}}(T) = \frac{I^2\rho(T)h}{abh(ab)} = \frac{I^2\rho(T)}{a^2b^2}, \tag{3}$$

where ρ(T) is the temperature dependence of the specific electrical resistance of the parts.

Taking the expression (2) into account, let us write down the approximation of the initial differential equation of thermal conductivity (1) for the i-th spatial spot and the j-th moment of time

$$c_i\left(T_i^*\right)\gamma_i\left(T_i^*\right)\frac{T_i - T_i^*}{t - t^*} = \frac{2}{\left(x_{i+1} - x_{i-1}\right)} \times \\ \times\left[\lambda_{i+1}\left(T_{i+1}^*\right)\frac{T_{i+1} - T_i}{x_{i+1} - x_i} - \lambda_i\left(T_i^*\right)\frac{T_i - T_{i-1}}{x_i - x_{i-1}}\right] + \\ + \frac{I^2\rho_i\left(T_i^*\right)}{a^2b^2}, \tag{4}$$

Table 1. Thermophysical characteristics of 12Kh18N10T steel and 2219 alloy

T, °C	12Kh18N10T			2219 alloy		
	λ, W/(m·K)	c, J/(kg·K)	ρ·10^{-9}, Ohm·m	λ, W/(m·K)	c, J/(kg·K)	ρ·10^{-9}, Ohm·m
20	15	450	725	130	0.8	55.3
100	16	462	792	142	0.86	62.4
200	18	496	861	155	0.92	72.2
300	19	517	920	163	1.05	77.2
400	21	538	976	167	1.05	85.6
500	23	550	1028	–	–	–
600	25	563	1075	–	–	–
700	27	575	1115	–	–	–

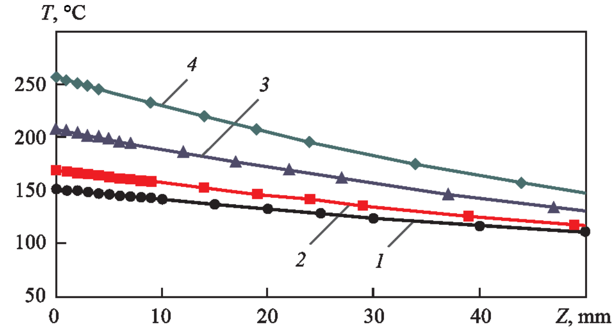

Figure 5. Calculated temperature fields during resistance heating through an intermediate insert of 12Kh18N10T steel of the thickness h_{in} = 2 (*2*), 6 (*3*), 12 (*4*) mm and without an insert (*1*) (h_{in} = = 0 mm) for the current density J = 10 A/mm² and t_h = 60 s (Z — distance from the ends of parts)

where T_i^* is the temperature in the calculation node at the previous time step (the step size is Δt); $c_i(T_i^*)$, $\gamma_i(T_i^*)$, $\lambda_i(T_i^*)$ is the temperature dependence of heat capacity, density, and thermal conductivity of the heated parts, respectively.

To calculate the temperature field, the following input data are entered into the mathematical model: geometric dimensions of welded parts and thickness of an intermediate insert; thermophysical characteristics of aluminium alloy and intermediate insert material (Table 1). The basic input parameters of heating mode are current density and heating time.

Using the developed mathematical model, the temperature fields during resistance heating of billets of 2219 aluminium alloy with a cross-section of 32×60 mm was calcualted depending on the thickness of the intermediate insert h_{in} of steel 12Kh18N10T at a heating time t_h = 60 s (Figure 5) and different current density J at t_h = 40 s (Figure 6).

Based on the obtained data, the dependence of the temperature of the characteristic spots of the welded joint on the current density during resistance heating without an insert and with the use of an intermediate insert of steel 12Kh18N10T was plotted (Figure 7).

The analysis of the obtained calculated temperature fields (Figure 5) shows that during resistance heating without inserting the parts of 2219 alloy with a cross-section of 32×60 mm at a time before t_h = 60 s at a current density J = 7.5 and 10 A/mm², the achievement of the specified temperature in the characteristic spots of the parts — in the contact zone and at a distance of 30 mm from the ends is not provided. The temperature distribution necessary for the formation of high-quality joints during resistance heating without an insert is achieved at a current density $J \geq 12.5$ A/mm² (Figure 6, *a*), which in practice causes significant energy losses for heating the secondary circuit of the welding machine and the need in using power sources of high capacity.

The results of the calculations shown in Figures 5 and 6, *b*, indicate a significant effect of using an intermediate insert during resistance heating — the temperature at both characteristic spots grows significantly at all the investigated values of current density, insert thickness and heating time. It was found that the efficiency of the resistance heating process through the intermediate insert depends on its thickness: the set temperature distribution in the parts of 2219 alloy at the current density J = 10 A/mm² and heating time t_h = 60 s is achieved at $h_{in} \geq 6$ mm.

For a set thickness of the insert, the efficiency of the heating process increases with a growth in the current density J (Figure 6, *b*), in particular, the set temperature distribution in the parts at h_{in} = 7 mm and heating time t_h = 40 s is achieved for all the investigated values of the current density J, except of J = 7.5 A/mm². A significant increase in temperature in the contact zone for all the values of the investigated parameters during heating through the insert should be noted, in particular at J = 12.5–15 A/mm² to T = 300–420 °C as compared to T = 180–270 °C during heating without an insert. The last fact is particularly important from the point of view of the stability of the flashing stages

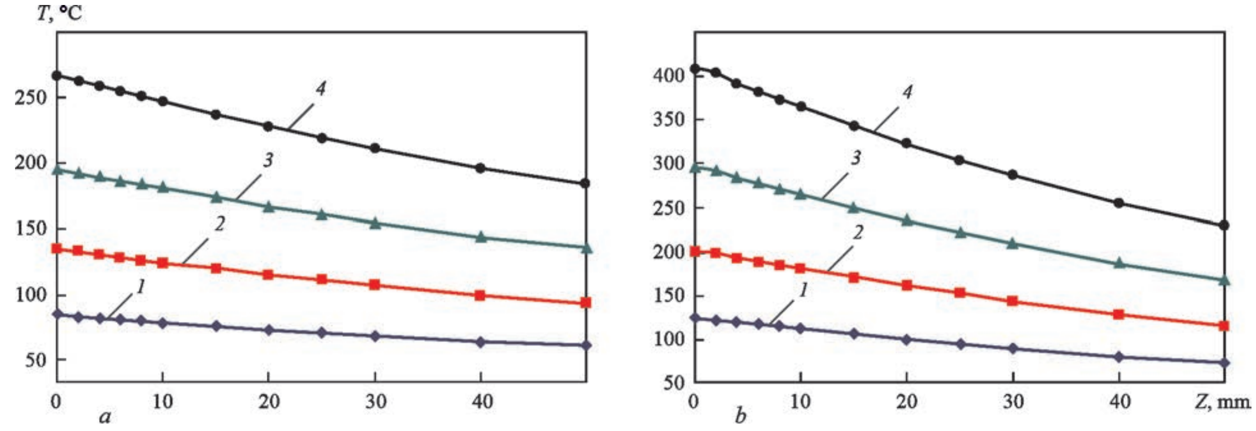

Figure 6. Calculated temperature fields during resistance heating without an insert (*a*) and through an intermediate insert of 12Kh18N10T steel of the thickness h_{in}= 7 mm (*b*) at t_h = 40 s and current density J = 7.5 (*1*), 10 (*2*), 12,5 (*3*), 15 (*4*) A/mm²

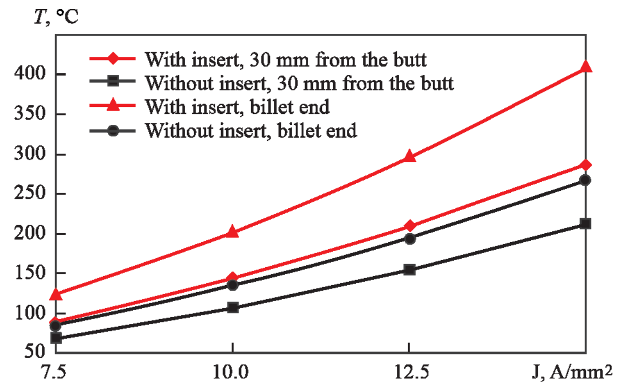

Figure 7. Calculated dependence of temperature of the characteristic spots of the welded joint on current density J in resistance heating using an intermediate insert of 12Kh18N10T steel and without it

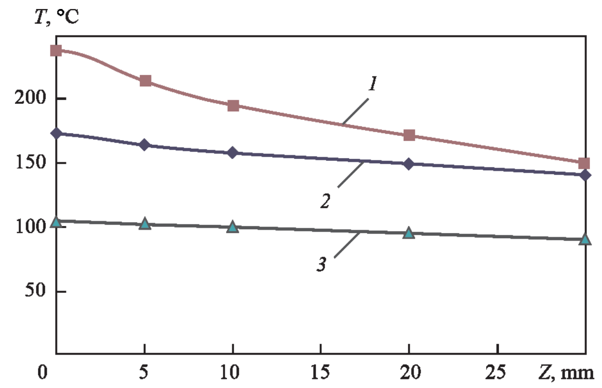

Figure 8. Temperature fields during resistance preheating using an intermediate insert of 12Kh18N10T steel of the thickness h_{in} = = 7 mm (*1*) and without an insert (*2*, *3*) during heating time $t_h = 40$ (*1*, *3*) and 85 s (*2*)

at a constant rate (see Figure 2, II stage) and intensive flashing before upsetting (IV stage), and from a practical point of view it makes it possible to guarantee the absence of welding defects (lacks of penetration, oxide films, matte spots) at a significantly lower power source of the welding machine.

The obtained results confirm the assumption that during resistance heating through an insert, an additional volume source of heat generation appears, which ensures more rapid heating of the metal at both characteristic spots — in the zone of intense deformation during upsetting and the contact zone of the parts and causes a decrease in energy loss for heating the secondary circuit of the welding machine.

EXPERIMENTAL STUDY OF RESISTANCE HEATING PROCESS

The experiments on studying thermal cycles of resistance heating of the parts with a cross-section of 32×60 mm of 2219 aluminium alloy were carried out at the secondary voltage of the transformer $U_{2o.-c} = 3$ V. The chromel-alumel thermocouples with a diameter of 0.5 mm were mounted in the parts at a distance of 5, 10, 20 and 30 mm from the ends on the inner side of the secondary circuit of the welding machine. The parts were heated directly (without an insert) and through an intermediate insert of 12Kh18N10T steel at a current density of about 10 A/mm^2 and heating time $t_h = 40$ and 85 s. Based on the calculation results, indicating the expediency of using the insert when its thickness is $h_{in} \geq 6$ mm, the experimental study of temperature fields was carried out at $h_{in} = 7$ mm.

The results of the experiments show that without using an intermediate insert at the set energy parameters of the preheating mode, it was impossible to achieve the required distribution of the temperature field during the time $t_h = 40$ and 85 s (Figure 8, curves *2*, *3*). At $t_h = 85$ s the process of heating almost transferred to a quasi-stationary state. The temperature in the contact zone at $t_h = 85$ s amounts to about 170 °C, and at a distance of 30 mm it was 140 °C. During heating of parts through the insert of 12Kh18N10T steel, the temperature in both characteristic spots is significantly increased and the temperature distribution required for the next stages of flashing is achieved during the time $t_h = 40$ s (Figure 8, curve *1*).

It is worth noting a significant increase in temperature in the contact zone while heating through the insert at $t_h = 40$ s, and a much higher gradient of temperature field as compared to heating without the insert at $t_h = 85$ s. The experimentally established growth of temperature in the contact zone is especially important in terms of stability of flashing stages and preventing the formation of defects in welded joints. In FBW of heat-strengthened alloys, the reduction in the duration of resistance heating contributes to minimizing negative structural and phase transformations in the heat-affected zone and causes maintaining of the values of strength, corrosion resistance and other service properties of welded products at a higher level [12].

Experimental study of temperature fields in the parts from 2219 alloy during their resistance heating using an intermediate insert of 12Kh18N10T steel at $t_h = 40$–85 s indicates the intensification and localization of the heat generation process in the contact area as compared to the heating process without the insert and confirm the calculation data according to the proposed generalizations.

Therefore, the results of the calculations and the experimental study of the temperature fields indicate an increase in the efficiency of the process of resistance preheating in FBW of aluminium alloys using an intermediate insert from the material with high electrical resistance. The mentioned effect is achieved by intensification and localization of the heat generation process in the contact zone of parts and a corresponding reduction in the «irrational» energy loss on heating of the secondary circuit of the welding machine.

CONCLUSIONS

1. The technological concept of flash-butt welding (FBW) of thick-walled parts from aluminium alloys with resistance preheating applying a reusable intermediate insert. The efficiency of the process of resistance preheating in FBW of 2219 aluminium alloy using an intermediate insert of 12Kh18N10T steel was investigated by calculation. As the criterion of the effectiveness of resistance heating, the achievement of the set temperature in the characteristic spots of the parts — in the contact zone and at a distance of 30 mm from the ends of the parts in the shortest time at the set value of the current density was considered.

2. It was established that as compared to direct resistance heating of parts using an intermediate insert of 12Kh18N10T steel, the temperature rises significantly at both characteristic spots at all investigated values of current density, thickness of the insert and heating time.

3. For the set thickness of the insert h_{in} in the studied range h_{in} = 2–12 mm the efficiency of the heating process increases with a growth in the current density J, and at the set value of J in the range J = 7.5–15 A/mm^2 — at an increase in the thickness of the insert.

4. A significant increase in the gradient of the temperature field in the parts during heating through the insert was established: the temperature in the contact zone at J = 12.5–15 A/mm^2 amounted to T = 300–420 °C as compared to T = 180–270 °C during heating without an insert. The mentioned result is important from the point of view of the stability of the subsequent stages of flashing in FBW and from a practical point of view, it makes it possible to guarantee the absence of welding defects at a significantly lower capacity of the power source of the welding machine.

5. An experimental study of the temperature fields in the parts of 2219 alloy during their resistance heating using an intermediate insert of 12Kh18N10T steel is confirmed by the calculated data and they indicate the intensification and localization of the heat generation process in the contact zone as compared to the heating process without an insert.

REFERENCES

1. Kuchuk-Yatsenko, S.I. (1992) *Flash butt welding*. Kyiv, Naukova Dumka [in Russian].
2. Kuchuk-Yatsenko, S.I., Chvertko, P.N., Semyonov, L.A. et al. (2010) Peculiarities of flash butt welding of high-strength aluminium alloy 2219. *The Paton Welding J.*, **3**, 7–9.
3. Kuchuk-Yatsenko, S.I., Gushchin, K.V. (2018) *Flash butt welding of high-strength aluminium-based alloys: Science of Materials: Achievements and Prospects*. Kyiv, Akademperiodyka [in Russian].
4. Weingrill, L., Krutzler, J., Enzinger, N. (2017) Temperature field evolution during flash-butt welding of railway rails. *Materials Sci. Forum*, 879, 2088–2093. DOI: 10.4028/www.scientific.net/MSF.879.2088.
5. https://www.schlattergroup.com/en/welding-machines/flash-butt-welding-machines-for-rails/
6. (2014) *Preheating burnoff flash butt welding method for welding large-section steel vehicle wheels*. Pat. CN103894717A.
7. Shi, S.-C., Wang, W.-C., Ko, D.-K. (2022) Influence of inclusions on mechanical properties in flash butt welding joint of high-strength low-alloy steel. *Metals*, 242(**12**), 1–13. DOI: 10.3390/met12020242.
8. Kuchuk-Yatsenko, V.S., Nakonechny, A.A., Sakhatsky, A.G. (2010) Resistance welding of steel reinforcement using composite insert. *The Paton Welding J.*, **4**, 34–36.
9. Kuchuk-Yatsenko, S.I., Zyakhor, I.V., Chernobaj, S.V. et al. (2015) Structure of γ-TiAl joints in resistance butt welding with application of interlayers. *The Paton Welding J.*, **9**, 5–12. DOI: 10.15407/tpwj2015.09.01.
10. Kuchuk-Yatsenko, S.I., Zyakhor, I.V., Nakonechny, A.A. et al. (2018) Resistance butt welding of titanium aluminide γ-TiAl with VT5 alloy. *The Paton Welding J.*, **9**, 2–6. DOI: 10.15407/tpwj2018.09.01.
11. Iurzhenko, M.V. (2019) Novel technological approach to butt welding «in closed volume» with heated tool of polymer multilayer composite pipes. *Visnyk KhNTU. Inzhenerni Nauky*, 68(**1**), 65–72 [in Russian].
12. Kuchuk-Yatsenko, S.I., Hushchyn, K.V., Ziakhor, I.V. et al. (2021) Structure and mechanical properties of 2219-T87 aluminium alloy joints produced by flash butt welding. *The Paton Welding J.*, **8**, 27–32. DOI: https://doi.org/10.37434/tpwj2021.08.06
13. Tkachenko, V.N. (2008) *Mathematical modeling, identification and control of technological processes of heat treatment of materials*. Kyiv, Naukova Dumka [in Russian].

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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