temperatures of 20 and 300 °C occurs in the zone of transition from the weld to base metal and propagates to the weld metal and thermomechanically affected zone (Figure 10). Recesses, which are indicative of a tough character of fracture of the specimens, can be easily seen on the fracture surfaces at high magnification.

Tensile strength of the joints is at a level of 370 MPa at a test temperature of 20 °C, and 197 MPa at 300 °C. The strength factor of the FSW joints is 0.63 at a test temperature of 20 °C and 0.57 at 300 °C. Elongation of the specimens remains at a level of 3.3 and 2.2 %, respectively, for the above test temperatures.

It should be noted in conclusion that due to formation of welds in the solid state, the FSW process allows the sound permanent joints to be produced on granulated, quasicrystalline and composite aluminium alloys without changing their phase-structural state. The granules containing oversaturated solid solution of refractory transition metals are uniformly distributed over the entire volume of the matrix in the weld metal, this providing tensile strength of such joints at a level of 70–80 % of that of the base material. No intermetallics are formed in the weld metal on aluminium alloy reinforced with the quasicrystalline particles, while the quasicrystals, the size of which remains within 100–200 nm, like in the base material, are uniformly distributed between grains of the α-Al matrix, thus providing welds with high strength and ductility values. No dissociation of the reinforcing particles is fixed in welding of composite materials, while their dispersion degree and uniformity of distribution in the weld metal remain at a level of the base material.

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FORCE EFFECT ON WELDED SURFACES INITIATED BY RUNNING OF SHS REACTION IN NANOLAYERED INTERLAYER

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The case of welding samples of titanium aluminide through nanostructured Ti/Al interlayer was used to calculate stresses arising in the surface layers of welded intermetallide samples, initiated by intensive heat evolution at running of the reaction of self-propagating high-temperature synthesis in the interlayer.

Keywords: *welding, nanolayered interlayer, reaction of self-propagating high-temperature synthesis, thermal stresses*

Studies [1, 2] show that an application of nanolayered foils based on elements forming intermetallides as interlayers significantly improves the conditions necessary for formation of solid phase permanent joints, i.e. heating temperature, delay time and pressure, applied for the joint obtaining, are reduced. Analysis of a diffusion zone of titanium aluminide based welded joint determined that its size increases 4 times in comparison with the diffusion zone, obtained in welding of intermetallide without the interlayer under similar conditions.

It is well-known fact that a reaction of self-propagating high-temperature synthesis (SHS), accompanied by intensive heat evolution, can be initiated in the process of heating. SHS reaction in Ti/Al foils, for example, took place in a mode of gas-free burning or heat explosion [3, 4] depending on initial temperature, thickness of the layers and their amount. Burning rate achieves 150 cm/s at 1100–1300 °C temperature. An intensity of heat evolution at running of SHS reaction, for example, in Ni/Al foils, can make 4 W/m^2. Such a pulse heat effect on the surface layers of welded materials can provoke in them appearance of the elastic stresses, besides local temperature increase, which also have influence on mass transfer processes similar to that appearing at impact effects on the welded surfaces [5, 6].

In this connection evaluation of a level of stresses which appear in the surface layers of samples being joined through the interlayer at initiation in it of SHS reaction was carried out in present study by example of γ-TiAl titanium aluminide.

The mathematical calculations were carried out for initial period of welding when temperature of the plates in the process of heating achieves the level of initiation temperature of SHS reaction under following conditions: size of welded samples of titanium aluminide is 10 × 10 × 5 mm; foil thickness being 20 μm; rate of preheating made 20 °C/min; pressure at preliminary contraction is 8 MPa; temperature of initiation of SHS reaction being 400 °C; foil «burning» front temperature made 1200 °C, running of SHS reaction simultaneously along the whole surface of nanolayered foil; time of running is $2\cdot10^{-5}$ s.

Two-dimensional problem was considered due to small size of the welded samples and their uniform heating on thickness. The foil was simulated as a gap δ_g between the plates.

Firstly, in the process of heating a temperature filed $T(x, y, t)$ in time was determined for analysis of stress-strain state in the studied plates of length L_x, height L_y and thickness δ (Figure 1):

$$\frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda \frac{\partial T}{\partial y}\right) = c\gamma \frac{\partial T}{\partial t}, \qquad (1)$$

where λ is the coefficient of heat conductance of the plate material; $c\gamma$ is the coefficient of volumetric heat capacity of the plate material; and t is the heating time.

Further, the problem on determination of stress and strain kinetics was solved. At that, the methods of sequential tracking in time with step Δt and finite-element method in space were used, i.e. given area was divided with step h_x and h_y and represented by population of rectangular element of $h_x \times h_y$ size.

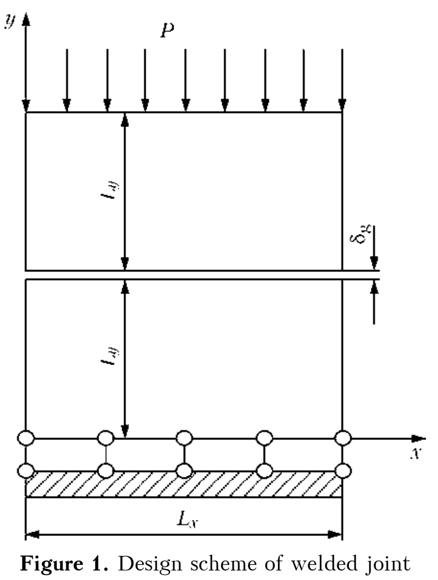

Figure 1. Design scheme of welded joint

The solution for each tracking step (in each point of time t) is found taking into account that was obtained for previous step $t - \Delta t$. The temperature in point of time t in the nods of mesh of finite-element space is determined through solving of a system of algebraic equations, obtained as a result of minimization of E_T functional in temperature in the nods of elements [7]:

$$E_T = -\frac{1}{2}\int_S \left[\lambda_x \left(\frac{\partial T}{\partial x}\right)^2 + \lambda_y \left(\frac{\partial T}{\partial y}\right)^2 + \frac{c\gamma}{\Delta t}\left(T - T_*\right)^2\right] \times$$
$$\times\, dx dy + \frac{1}{2}\int_\Gamma \beta_n (T - T_{env})^2 d\Gamma; \qquad (2)$$
$$\partial E_T / \partial T_{mn} = 0, \quad m = 1, 2, \ldots,$$

$n = 1, 2 \ldots$ is the numeration of nods in x, y direction,

where $T_* = T(x, y, t - \Delta t)$ is the already known temperature in point of time $t - \Delta t$ starting form the initial one ($t = 0$); S is the considered area; Γ are the outside boundaries of part; β_n is the coefficient of heat exchange with environment of T_{env} temperature.

The derivatives $\partial T/\partial x$, $\partial T/\partial y$ are expressed through temperature in the nods for each rectangular element. Thus, the integral of area S is substituted by sum of finite element integrals of area ΔS. The same is done with integral Γ in surface.

Let us consider an algorithm for solving of mechanical problem at loading stage corresponding to point of time t, assuming that the solution is completely known relative to stress tensors σ_{ij}, strain ε_{ij} and movements U_i in scope of described above two-dimensional stress state at $t_* = t - \Delta t$.

For this, expression (2) is integrated in time in the ranges from $t - \Delta t$ to t:

$$\Delta\varepsilon_{ij} = \left\{\frac{\sigma_{ij} - \delta_{ij}\sigma}{2G} + \delta_{ij}[K\sigma + \alpha_T(T - T_0)]\right\}_t -$$
$$- \left\{\frac{\sigma_{ij} - \delta_{ij}\sigma}{2G} + \delta_{ij}[K\sigma + \alpha_T(T - T_0)]\right\}_{t - \Delta t} + \qquad (3)$$
$$+ \Delta\lambda(\overline{\sigma_{ij} - \delta_{ij}\sigma}),$$

where $\delta_{ij}\sigma$ is the spherical tensor (here σ is the average pressure in a point; δ_{ij} is the unit function); G is the shear modulus; K is the modulus of volume compression equal $(1-2\nu)/E$; ν is the Poisson's ratio; E is the Young's modulus; α_T is the coefficient of thermal linear expansion (CTLE); T_0 is the initial temperature; $\overline{\sigma_{ij} - \delta_{ij}\sigma}$ is the average value of $\sigma_{ij} - \delta_{ij}\sigma$ at interval from $t - \Delta T$ to t, calculated based on average value of specific integral.

If Δt value is small then $\overline{\sigma_{ij} - \delta_{ij}\sigma}$ value can be substituted by desired value in the point of time t. Than, the following will be obtained for two-dimensional stressed state instead of (3):

$$\Delta\varepsilon_{xx} = B_1\sigma_{xx} + B_2\sigma_{yy} - b_{xx};$$
$$\Delta\varepsilon_{yy} = B_1\sigma_{yy} + B_2\sigma_{xx} - b_{yy}; \quad (4)$$
$$\Delta\varepsilon_{xy} = \psi\sigma_{xy} - b_{xy},$$

where σ_{xx}, σ_{yy} are the normal stresses; σ_{xy} are the tangential stresses;

$$B_1 = \frac{2\psi + K}{3}; \quad B_2 = \frac{K - \psi}{3}; \quad \psi = \frac{1}{2G} + \Delta\lambda;$$
$$b_{ij} = \left(\frac{\sigma_{ij}}{2G}\right)_{t-\Delta t} + \delta_{ij}\left[\sigma\left(K - \frac{1}{2G}\right)\right]_{t-\Delta t};$$
$$\delta_{ij}\Delta\varphi,\ i, j = x, y;\ \Delta\varphi = [\alpha_T T - T_0)]_t - [\alpha_T(T - T_0)]_{t-\Delta t},$$

where φ is the function of temperature elongation.

It can be seen, hence, that b_{ij} is determined by a solution in the point of time $t - \Delta t$ and known value of $\Delta\varphi$. Function ψ of a state of material in element volume in the point of time t contains nonlinearity, connected with yield condition.

It is assumed that value $\psi(x, y, t)$ is known. Solving (4) relative to stresses, the following is obtained:

$$\sigma_{xx} = A_1\Delta\varepsilon_{xx} + A_2\Delta\varepsilon_{yy} + Y_{xx};$$
$$\sigma_{yy} = A_1\Delta\varepsilon_{yy} + A_2\Delta\varepsilon_{xx} + Y_{yy}; \quad (5)$$
$$\sigma_{xy} = \frac{1}{\psi}\Delta\varepsilon_{xy} + Y_{xy}; \quad \sigma_{zz} = \sigma_{xz} = \sigma_{yz} = 0,$$

where $A_1 = \dfrac{2\psi + K}{\psi(\psi + 2K)}$; $A_2 = \dfrac{\psi - K}{\psi(\psi + 2K)}$; $Y_{xx} = A_1 b_{xx} + A_2 b_{yy}$; $Y_{yy} = A_1 b_{yy} + A_2 b_{xx}$; $Y_{xy} = b_{xy}/\psi$.

The relationship between deformation increment $\Delta\varepsilon_{ij}$ and components of vector of movement increment ΔU_i can be presented in a form of

$$\Delta\varepsilon_{xx} = \frac{\partial\Delta U_x}{\partial x}; \quad \Delta\varepsilon_{yy} = \frac{\partial\Delta U_y}{\partial y};$$
$$\Delta\varepsilon_{xy} = \frac{1}{2}\left(\frac{\partial\Delta U_y}{\partial x} + \frac{\partial\Delta U_x}{\partial y}\right). \quad (6)$$

Equation of consistency of strains looks like

$$\frac{\partial^2\Delta\varepsilon_{xx}}{\partial y^2} + \frac{\partial^2\Delta\varepsilon_{yy}}{\partial x^2} = 2\,\frac{\partial^2\Delta\varepsilon_{xy}}{\partial x\partial y}. \quad (7)$$

Equilibrium equation can be represented as

$$\frac{\partial\sigma_{xx}}{\partial x} + \frac{\partial\sigma_{xy}}{\partial y} = 0; \quad \frac{\partial\sigma_{xy}}{\partial x} + \frac{\partial\sigma_{yy}}{\partial y} = 0. \quad (8)$$

The conditions on plate boundary in a point with normal n, i.e. in part of boundary where the forces Γ_P are applied, can be found using equations

$$\sigma_{xx}\cos(n, x) + \sigma_{xy}\cos(n, y) = P_x;$$
$$\sigma_{xy}\cos(n, x) + \sigma_{yy}\cos(n, y) = P_y, \quad (9)$$

where P_x, P_y are the projections of application of forces on axes x and y.

For the part of boundary where mixed boundary conditions Γ_u are set

$$\Delta U_x = \Delta U_x^0; \quad \Delta U_y = \Delta U_y^0. \quad (10)$$

A proper combination of conditions (9) and (10) provides mixed conditions in part of boundary Γ_{Pu}. Equations (5)–(10) at known value of $\psi(x, y, t)$ completely determine differential formulation of a boundary-value problem on calculation of σ_{ij}, ε_{ij} and U_i.

A variation formulation of this problem is considered that is important in realizing of solution by finite-element method. For this the functional is used:

$$E_1 = -\frac{1}{2}\int_S \{(\sigma_{xx} + Y_{xx})\Delta\varepsilon_{xx} + (\sigma_{yy} + Y_{yy})\Delta\varepsilon_{yy} + $$
$$+ 2(\sigma_{xy} + Y_{xy})\Delta\varepsilon_{xy}\}dxdy + \int_\Gamma P_i\Delta U_i d\Gamma. \quad (11)$$

It follows form studies [7, 8] that an absolute minimum E_1 for kinematically possible $\Delta\varepsilon_{ij}$ meets an actual distribution of the strain increments $\Delta\varepsilon_{ij}$ and corresponding to them increments ΔU_i which are the solutions of boundary-value problem (5)–(10).

The area integral S taking into account expression (11) is substituted by sum of the finite element integrals ΔS, strain $\Delta\varepsilon_{ij}$ are expressed through ΔU_i and stresses σ_{ij} are shown through $\Delta\varepsilon_{ij}$. The derivatives in (6) for each ΔS are expressed through ΔU_i in the nod points. The similar is done with integral in Γ. Thus, functional E_1 will be shown by quadratic form through unknown values of ΔU_x and ΔU_y in mesh nods.

Minimization of $\partial E_1/\partial\Delta U_x = 0$, $\partial E_1/\partial\Delta U_y = 0$ provides the system of algebraic equations being linear relatively to ΔU_i (at known function ψ).

$\Delta\varepsilon_{ij}$ and σ_{ij} are calculated after determination of ΔU_i. The function ψ is specified by obtained values of σ_{ij}. Different iteration processes are possible for this purpose among which a process, described in studies [7, 8], being sufficiently effective.

Thermo-physical and mechanical characteristics of titanium aluminide, given below, were used for calculation of elastoplastic stresses, occurring in the samples from γ-TiAl aluminide titanium at the moment of running of SHS reaction in the nanolayered foil.

Coefficient of heat conductance of plate material λ, $J/(m^3 \cdot K)$ [9] 0.25
Coefficient of volumetric heat capacity of plate material $c\gamma$, $J/(m^3 \cdot K)$ [9] 0.8
Yield strength $\sigma_{0.2}$, MPa [10] 510
Young's modulus E, MPa [11] .... $1.2 \cdot 10^5$
CTLE α_T, °C^{-1} [12] .... $10.8 \cdot 10^{-6}$

Coefficients λ and $c\gamma$ for titanium aluminide were taken as an average from given values for titanium and aluminide. Character of change of stressed state and level of microstrains of the surface layer of joined materials at running of SHS reaction in the nanolayered foil is shown in Figure 2. It can be seen from Figure that a jump in compression stresses (σ_{xx} = = 240 MPa) takes place at rapid increase of temperature up to 1200 °C in the joint. They are changed by tensile ones which reach 575 MPa for 0.3 s. Running

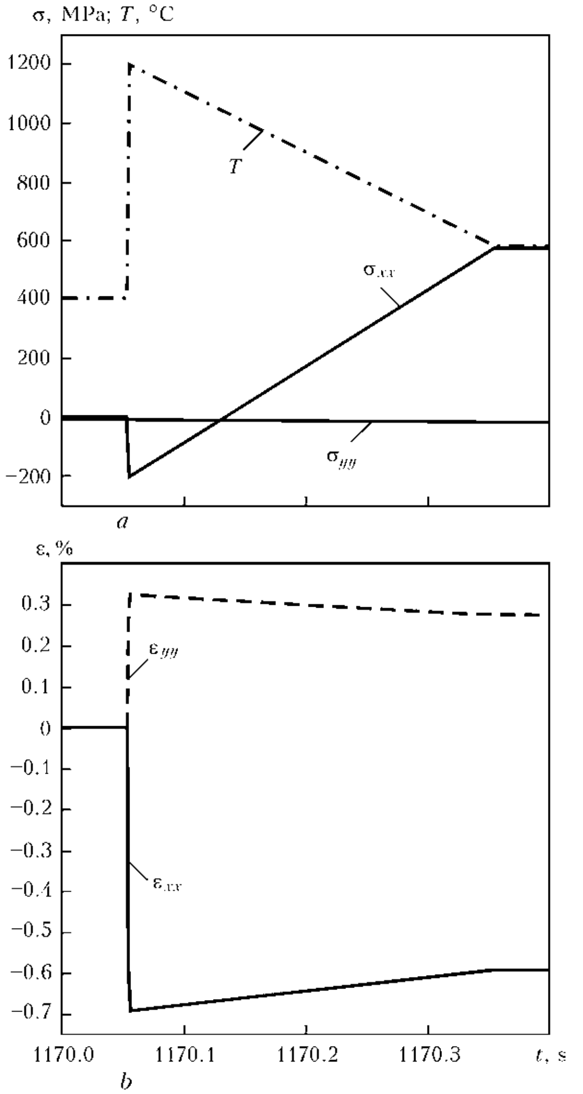

Figure 2. Curves of stresses σ_{xx} and σ_{yy} (*a*) and strains ε_{xx} and δ_{yy} (*b*) in near-contact volumes of the welded plates at running of SHS reaction

of SHS reaction also results in a rise of σ_{yy} from 8 to 18 MPa that exceeds the value of pressure of preliminary contraction more than 2 times. The calculated values of microstrains of the near-contact surface layer ($\delta \sim 20$ μm) make not more than 0.7 % (Figure 2, *b*).

Therefore, obtained calculation results indicate that running of SHS reaction in the interlayer results in a significantly intensive dynamic deformation effect on the welded surfaces. A thermal «hit» together with local increase of temperature activates the diffusion processes in the surface layers of welded materials and provides conditions for formation of permanent joints from difficult to weld materials.

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