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PREDICTION OF SUSCEPTIBILITY OF WELDED JOINTS OF TITAN γ-ALUMINIDE BASED ALLOY TO COLD CRACKING IN ELECTRON-BEAM WELDING

Numerical simulation of susceptibility of various thickness plates from titan γ-aluminide based alloy to cold cracking under electron-beam butt welding is carried out. It is revealed, that the cold crack nucleation during welding may happen both at cooling stage as a result of high stresses in the weld seam area and heat-affected zone, and also at heating stage, when the tensile balancing stresses field is formed at the periphery of welded structure.

It is shown and confirmed experimentally, that uniform heating before welding and controlled cooling-down of welded specimen permit to obtain the defect-free joints of various thickness plates. [dx.doi.org/10.29010/88.9]

Keywords: *titan γ-aluminide; electron-beam welding; stress-strain state; cold cracks; controlled cooling-down.*

Introduction

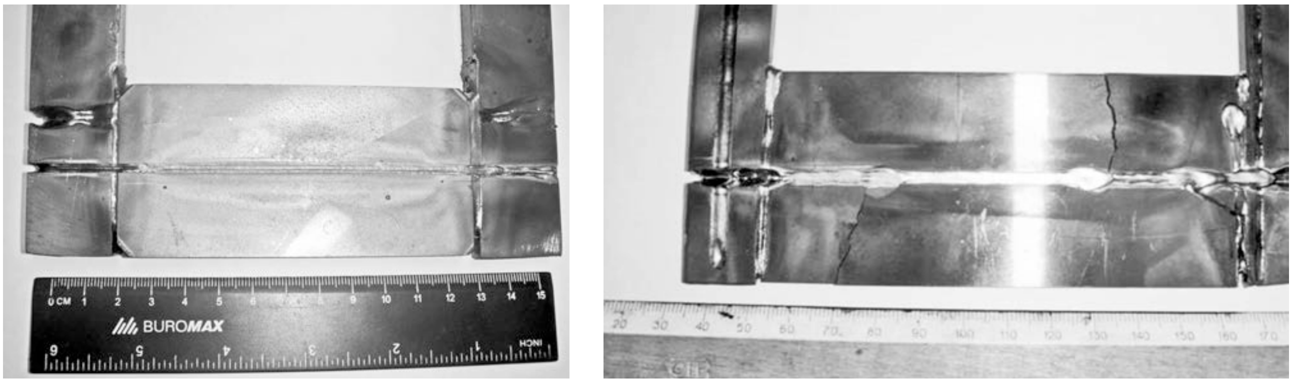
At present time the complex doped alloys on titan γ-aluminide base are used in production of engine components (pistons, valves, etc.), where the requirements necessary are high heat-resistance and low specific gravity. At that, the natural-imposed necessity arises to obtain the permanent joining of separate elements and it further effective usage. For this goal, particularly, the electron-beam welding (EBW) is widely use, which permit obtaining the parts with small residual distortion and with minimum metal contamination by interstitial impurities. But under such welding method the high cooling rate of weld seam and heat-affected zone (HAZ), as well as the increased sensitivity of complex doped titan alloys to the thermal affect, result sometimes in reduced ductility of joint in after-welding condition, which may lead to defects nucleation of cold cracks type.

Problem statement

Effectiveness of preliminary heating of various thickness plates as applied to the intermetallide titan alloys welding was shown by the authors before [1]. It permits to reduce the temporary tensile stresses and obtain more ductile microstructure, that is to say, to weld effectively by electron beam, particularly, the plates of 10 mm thickness (see. the Fig. 1, *a*).

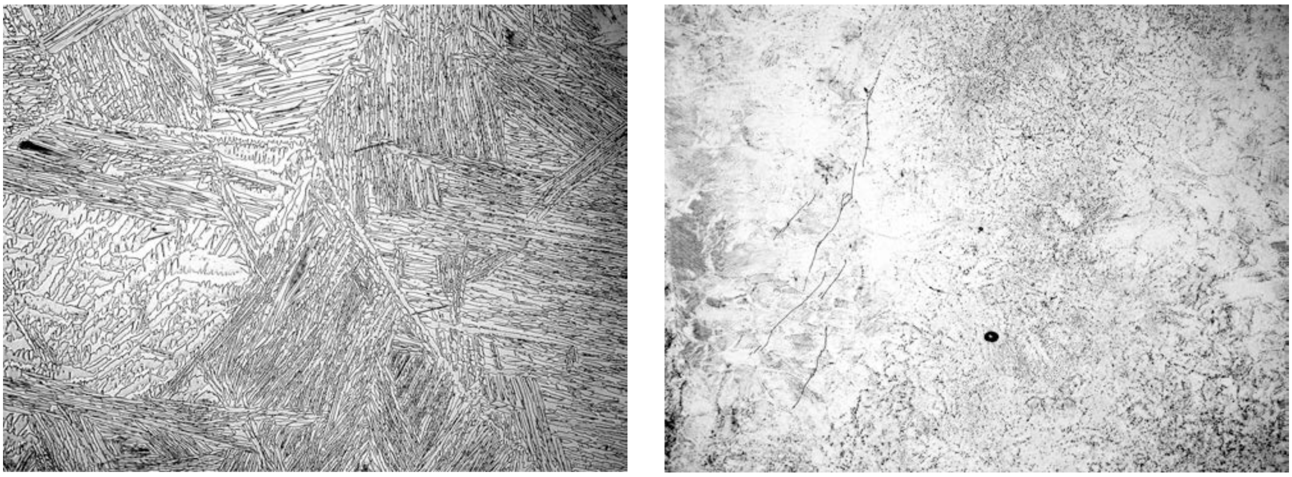
On the base of results of numerical investigations the necessary temperatures of preliminary heating of welding area were determined. Based on the same recommendations, the cold cracks were arisen in welded joints during welding of thinner plates (see the Fig. 1, *b*). The EBW was carried out in regime of dagger penetration and, as the results of microstructure investigations of 10 mm thickness welded joints showed (see the Fig. 2, *a*), the penetration is enough uniformly in depth and, hence, stress and strain fields are in conformity with conditions of plain stress state.

It is necessary to note the heterogeneity of seam metal structure in form of colonies of $(\gamma + \alpha_2)$ phase during the EBW welding of 3 mm thickness plate, as well as it was revealed a great number of cracks with lengths from 100 μm to 300 μm (see the Fig. 2, *b*). During the welding of 10 mm thickness plates, i.e. under more slow cooling-down, the transformation of α phase into lamellar $(\gamma + \alpha_2)$ phase take place, as well as some quantity of β_2-phase, which is ordered structure of β_0-phase, retains in the alloy. This phase improves the alloy strength and ductility, as well as blocks the nucleation and propagation of cracks in α_2-phase due to stresses decrease. Thus, from the mathematic point of view, kinetics of stresses is not depening from thickness of plates welded. Notwithstanding, a number of experimental investigations confirms, that 3 mm thickness plates from titan γ-aluminide alloy are more susceptible to cold cracking in the EBW realization in comparison with 10 mm thickness plates. Moreover, it was revealed, that in some cases the cracking of 3 mm thickness samples took place at the heating stage up to melting temperature. As is well



a *b*

Fig. 1. External appearance of samples from titan γ-aluminide based alloy welded by electron-beam welding:
a — defect-free, 10 mm thickness; *b* — 3 mm thickness with cold cracks formed after welding



a *b*

Fig. 2. Microstructure of welded joint metal of titan γ-aluminide based alloy after the EBW:
a — 10 mm thickness plate; *b* — 3 mm thickness plate; ×100

known, at that the compressive normal stresses only are formed in the welding zone, which do not result in cracking formation danger. Thus, in order to optimize the EBW regimes, the additional investigations in the EBW of titan γ-aluminide based alloy plates of various thicknesses are necessary, which is the purpose of the present article.

Results of investigation

In order to solve the problem assigned, a complex approach of mathematical modeling of the EBW process with proper experimental confirmation of results, obtained during the welding, was used in the present article. Intermetallide of TiAl system, mas. % (Ti — 52.82%, Al — 28.80%, Nb — 11.72%, Cr — 3.51%, Zr — 3.15%, its physical and mechanical properties are in the Table 1), which pertains to the new class of β-hardening intermetallide alloys, was used for laboratory investigations. Structure of initial material, obtained by the electron-beam welding method, consists of γ-TiAl+α_2-Ti_3Al. At that, addition of 11.72 % of niobium (which is β-stabilizer) into the alloy results in increase of more ductile ordered β_0(B2)-phase which existence permits to affect the structure by means of thermal processing and, correspondingly, to affect the mechanical properties of metal.

In the frame of the present article the samples of 25×100 mm dimensions and 3 mm and 10 mm thicknesses (see the Fig. 1, *a*) were investigated, which welding was carried out with УЛ-144 plant (volume 2.2 m^3, plant power supply unit ЭЛА60/60 of 60 kW electric power with 60 kV accelerating voltage, residual pressure in the chamber was not more than $5{\cdot}10^{-5}$ mm Hg) by using the following regime: U = 60 kV; I = 35 mA; v_{weld} =7 mm·s^{-1}. Kinetics of temperature field during welding process was measured by means of thermocouples installed onto lower surface of the plate near the butt joint. Scheme of welding process is presented in the Fig. 3.

Table 1

Temperature dependences of physical and mechanical properties of Ti — 52.82 mas. %; Al — 28.8 mas. %; Nb — 11.72 mas. %; Cr — 3.51 mas. %; Zr — 3.16 mas. % alloy

T, °C	$E\cdot10^{-5}$, MPa	σ_T, MPa	$\alpha\cdot10_4$, °C^{-1}	λ, J/(m·s·°C)	$C_\gamma\cdot10^{-6}$, J/(m^3·°C)
20	1.725	331.0	0.110	12.5	2.03000
100	1.690	328.0	0.110	12.5	2.59840
200	1.643	325.0	0.110	14.0	2.63900
300	1.586	322.0	0.110	15.0	2.67960
400	1.517	319.0	0.110	15.5	2.72020
500	1.441	316.0	0.110	15.5	2.76080
600	1.358	313.0	0.110	17.7	2.78110
700	1.269	310.0	0.110	20.1	2.78922
800	1.174	260.0	0.110	22.5	2.79328
900	1.174	150.0	0.110	22.0	2.79734
1000	0.974	100.0	0.110	22.0	2.84200
1100	0.740	50.0	0.110	22.0	2.84200
1200	0.070	50.0	0.110	22.0	2.84200

For mathematical modeling of thermal deformation of welded samples during the welding, the generally used physical assumptions and mathematical models of temperature field kinetics and elastoplastic strain of continuous medium were used. As previously stated, for all thicknesses of plates welded the EBW is realized in keyhole regime, thus temperature field may be considered as uniform by thickness. Thus, temperature kinetics during the EBW may be described by means of non-stationary heat conduction equation:

$$C_\gamma(T)\cdot\frac{\partial T}{\partial t}=\nabla\left[\lambda(T)\cdot\nabla T\right]-\frac{\alpha\cdot(T-T_0)+\varepsilon_0\cdot\sigma_{SF}\cdot\left(T^4-T_0^4\right)}{\delta}+q, \quad (1)$$

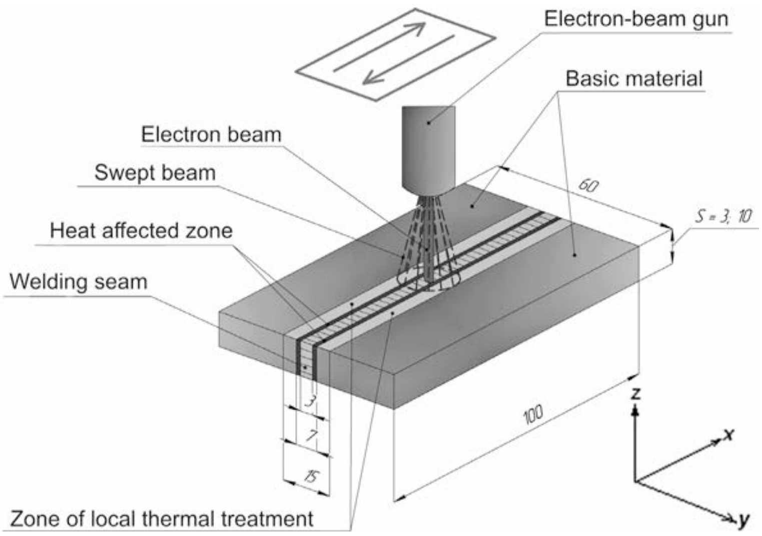


Fig. 3. Scheme of electron-beam butt welding of titan γ-aluminide based alloy plates with preliminary local heating of edges [2]

where C_γ, λ are temperature dependent the metal volumetric heat capacity and heat conductivity, respectively; T — temperature of structure at the t time moment in the point with coordinates (x, y); α_T — coefficient of surface heat emission to the fixtures (supporting table); ε_0 — emissivity factor of the plates surface; σ_{SB} — Stefan-Boltzmann constant; T_0 — ambient temperature; q — heat flux from source of welding heating in the surface area considered, which in case of keyhole penetration during the EBW realization may be described as follows:

$$q=\frac{\eta\cdot U\cdot I}{\pi\cdot\delta\cdot K_s}\cdot\exp\left(-\frac{x^2+y^2}{K_s}\right), \quad (2)$$

where η — efficiency of welding heating source; U — accelerating voltage on electron-beam gun; I — welding current; K_s — coefficient of energy flux concentration in electron beam.

Boundary conditions of heat conductivity equation (1) for considered case of the EBW in vacuum are as follows:

$$-\lambda(T)\cdot\frac{\partial T}{\partial n}=\begin{cases}\alpha_T\cdot\left(T-T_C\right), \text{ in area of contact with fixtures}\\ \varepsilon_0\cdot\sigma_{SF}\cdot\left(T^4-T_C^4\right), \text{ onto free surfaces}\end{cases} \quad (3)$$

where n — normal to the structure surface.

By numerical solution of equations (1)—(3) in frames of the present article the kinetics of temperature fields in welded plates from considered titan alloy under preliminary heating, welding and subsequent cooling-down up to room temperature is determined. On base of these numerical results the kinetics of stress-strain state (SSS) of the sample welded was predicted. In the basis of this investigation stage the finite-element solution of non-stationary thermoplasticity problem was laid down, for which the typical mechanisms of thermal deforming were considered, namely, by presentation of strain tensor ε_{ij} ($i, j = x, y, z$) as sum of appropriate components [3]:

$$d\varepsilon_{ij} = d\varepsilon_{ij}^{e} + d\varepsilon_{ij}^{p} + \delta_{ij} \cdot d\varepsilon_{ij}^{T}, \tag{4}$$

where $d\varepsilon_{ij}^{e}$, $d\varepsilon_{ij}^{p}$, $d\varepsilon_{ij}^{T}$ — components of strain tensor increments, which are determined by elastic mechanism of deforming, plastic flow and temperature expansion, respectively.

Relation between tensors of stresses σ_{ij} and deformations ε_{ij} in frames of finite-elements description is presented in the next form [4]:

$$\Delta\varepsilon_{ij} = \Psi \cdot \left(\sigma_{ij} - \delta_{ij} \cdot \sigma_m\right) + \delta_{ij} \cdot \left(K \cdot \sigma_m + \Delta\varepsilon_T\right) - \\ - \frac{1}{2 \cdot G} \cdot \left(\sigma_{ij} - \delta_{ij} \cdot \sigma_m\right)^* + \left(K \cdot \sigma_m\right)^*, \tag{5}$$

$$\Delta\varepsilon_{ij} = \left(\Psi - \frac{1}{2 \cdot G}\right) \cdot \left(\sigma_{ij} - \delta_{ij} \cdot \sigma_m\right), \tag{6}$$

$$\sigma_{ij} = \frac{1}{\Psi} \cdot \left(\Delta\varepsilon_{ij} + \delta_{ij} \cdot \frac{\Psi - K}{K} \cdot \Delta\varepsilon\right) + J_{ij}, \tag{7}$$

where $K = (1 - 2 \cdot \nu)/E$, $G = 0{,}5 \cdot E/(1 + \nu)$, E — Young modulus; υ — Poisson ratio; $\sigma_m = \sigma_{ii}/3$ — membrane stress; Ψ — material state function, which is determined by iteration for satisfaction of plastic flow conditions:

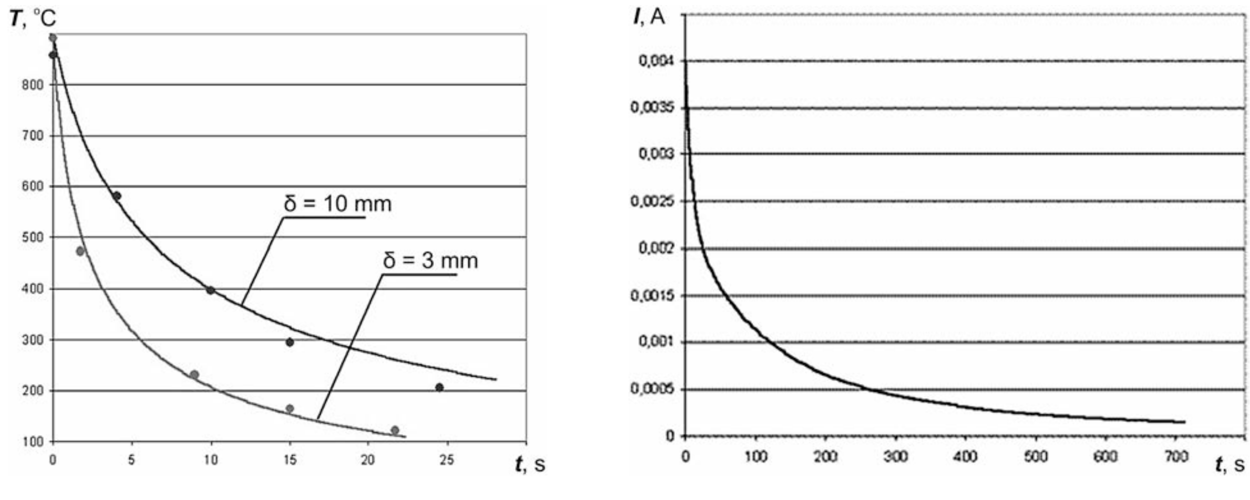
$$\Psi = \frac{1}{2 \cdot G}, \text{ if } \sigma_i < \sigma_s = \sigma_{\text{т}}; \\ \Psi > \frac{1}{2 \cdot G}, \text{ if } \sigma_i = \sigma_s; \\ \text{state } \sigma_i > \sigma_s \text{ is unacceptable,} \tag{8}$$

$\sigma_{\text{т}}$ — material yield stress; $\sigma_i = \sqrt{\sigma_{ij} \cdot \sigma_{ij}/2}$ — stress intensity.

Numerical solution of the SSS sample prediction problem during welding was carried out by means of tracing of elastoplastic strains in frame of finite-elements description [5], for which 8-node elements in Cartesian coordinate system were used. Dimensions of finite elements and time fragmentation were determined by Panov rule and were accepted in range from 0.1 mm in welded joint area to 1.0 mm in the sample's periphery.

The first stage of investigation was in determining of peculiarities of temperature fields kinetics during the EBW of various thickness plates from alloy based on titan γ-aluminide. It should be noted that the heating of δ = 10 mm thickness plates (with preliminary heating-up to T_{ph} =450 °C and annealing at 900 °C within 5 min, U = 60 kV; I = 100 mA; v_{weld} = 7 mm·s^{-1}) and δ = 3 mm plates (with preliminary heating-up to T_{ph} = 450 °C and annealing at 900 °C within 5 min, U = 60 kV; I = 35 mA; v_{weld} = 7 mm·s^{-1}) are similar, but cooling-down kinetics is different essentially, which are confirmed by both numerical and experimental investigations, demonstrating good correspondence (see. the Fig. 4, *a*). This is connected with such fact, that the heat removal rate through the surface of sample welded in vacuum is limited by heat feeding from metal to the surface owing to heat conductivity mechanism, because λ value for titan is typically low. Thus, δ = 10 mm thickness welded joints are cooled-down much slow, than more thin 3 mm plate, which determines the favorite conditions in terms of absence of meta-stable phases formation, increasing the metal ability to the cold cracking. In order to ensure necessary metal cooling regimes after welding and after-welding annealing, it was proposed the use of controlled cooling-down: after welding termination the electron beam was defocused and heating of surface of all sample was continued at regimes permitting to compensate the extra heat removal and to provide the same cooling-down cycle, which was realized during welding of δ = 10 mm thickness plates and which was supposed as an optimal one. As the calculation results showed, for this case the heating current should vary in time after welding according with the following dependence, presented in the Fig. 4, *b*.

Welding of a number of δ = 3 mm thickness samples with recommended controlled cooling-down was carried out. In spite of the fact that temperature cycles during welding repeat the cycles realized during welding of δ = 10 mm plates, it was impossible to avoid the cold cracks formation at the heating stage. It was supposed by the authors, that the welded 3 mm thickness joints was subjected to general bending strains due to peculiarities of sample fixing in the fixtures (see diagram in the Fig. 5, *a*) with the result of additional longitudinal bending stresses formation. As the calculation results shown, the considerable residual bending of welded joints (more than 3 mm) is necessary for this. Other possible explanation of cracks nucleation at the heating stage was the presence of torsion general strains in 3 mm thickness samples (Fig. 5, *a*) and, as a result, formation of shearing stress field. The authors accomplished simulation of three-dimensional stress field for the EBW of δ = 3 mm plates in torsion conditions (deviation of edges parallelism about 1 mm), but the results obtained, which are presented in the Fig. 6, showed, that it not leads to the considerable



a *b*

Fig. 4. Kinetics of cooling-down of various thickness plates after the EBW (*a*) and recommended regime (*b*) of after-welding heating with scanning source for δ = 3 mm plate in case of controlled cooling-down in the same regime as for δ = 10 mm plate, in order to eliminate the cold cracking formation

shearing stresses which may cause the shearing cracks nucleation.

As the results of numerical simulation demonstrated, the explanation of revealed cold cracking phenomena of more thin plates at heating stage is connected with the method of sample preliminary heating before welding. It was mentioned before, that preliminary heating was carried out in the welding area only per some beam passes at low heating power, until the thermocouple onto lower surface begin to fix the achievement of required temperature T_{ph} (about 450 °C). At that, 10 mm thickness sample warms thoroughly not only deep down the welded joint, but at the periphery also, whereas for 3 mm thickness sample the periphery remains cold enough. As may be seen from the calculation results (see the Fig. 7), both at the heating stage, and at the stationary regime of welding, the positive axial stresses are formed, which balance the compressive stresses in welded joint area and are potential place of cold cracks nucleation. More rational is the use of scanning preliminary heating over the entire surface of sample (see the Fig. 8), which permits, at first, to reduce noticeably the level of temporary stresses at all stages of the EBW (see the Fig. 9), secondly, to obtain more smooth curves of temperature cycles at the heating stage.

Based on results of numerical and experimental analysis obtained, for welding of δ = 3 mm thickness plates from titan γ-aluminide based alloy it is recommended together with controlled cooling-down by mentioned regimes (see the Fig. 4, *b*) to use the preliminary heating up to 450 °C over the entire surface of sample. In pursuance of these technological recommendation, the defect-free welding joint of δ = 3 mm thickness plates was obtained (see the Fig. 10), which confirms the correctness of conclusions drawn.

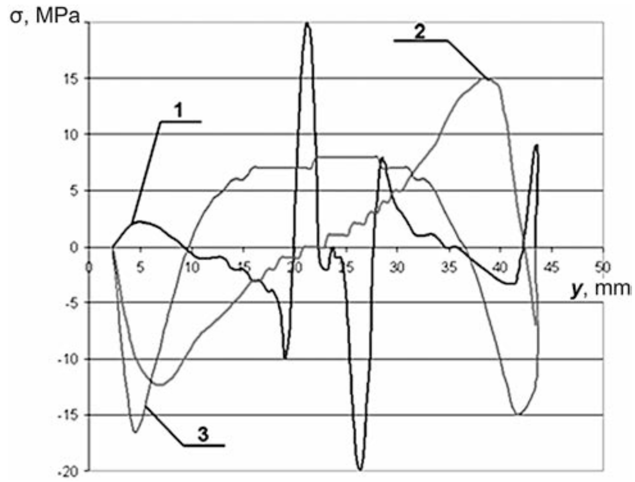


Fig. 6. Distribution of shearing stresses τ_{xy} (*1*), τ_{xz} (*2*), τ_{yz} (*3*), which are formed in welded sample (δ = 3 mm), taking into account the torsion strains

Conclusions

1. The complex of mathematical models and computer programs for numerical prediction of temperature field kinetics in one-pass EBW of plates from titan γ-aluminide based alloy is developed, comparison of calculated results with laboratory experiment data is carried out, and enough accuracy of the models proposed is demonstrated.

2. It is shown, that the main difference between temperature cycles of the EBW of various thickness plates is essentially lower cooling rate of 10 mm thickness plates. It promotes more favorable conditions of structural composition of considered intermetallide titan alloy, which results in reduction of metal susceptibility to cold cracking after the EBW.

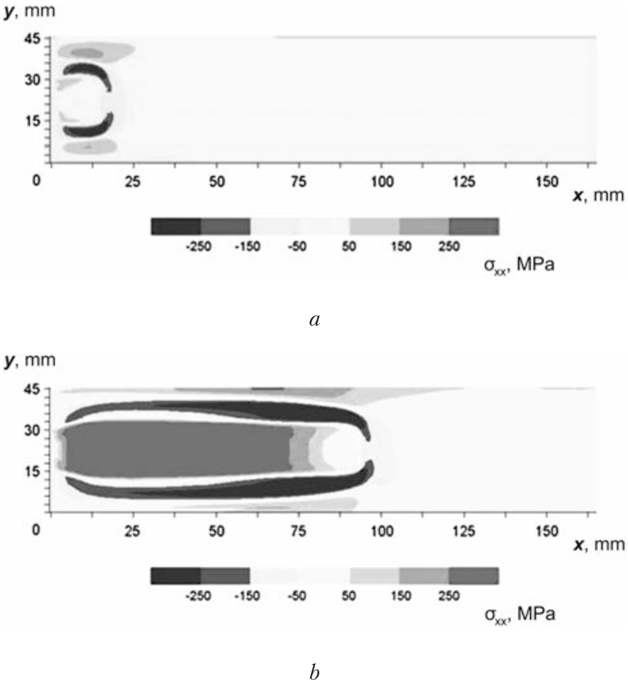


Fig. 7. Distribution of longitudinal stresses in the welded sample: *a* — at initial welding stage; *b* — in stationary thermal regime under local preliminary heating of welding area

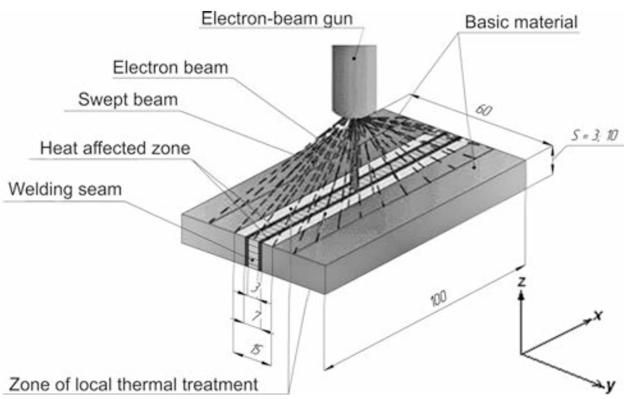


Fig. 8. Alternative scheme of electron-beam butt welding of titan γ-aluminide based alloy plates with uniform preliminary heating

3. The regimes of controlled cooling-down of 3 mm thickness plates, permitting to compensate the excess surface heat emission and to repeat the temperature cycles, observed during welding of 10 mm thickness plates, are proposed, which allow to avoid the cold cracks formation at the cooling-down stage after the EBW. For this goal it is recommended to carry out the heating after welding and thermal processing by defocused electron beam with gradual reduction of its power.

4. The complex of mathematical models and computer programs for numerical prediction of stress-strain state kinetics for various thickness plates from titan γ-aluminide based alloy during the EBW is developed.

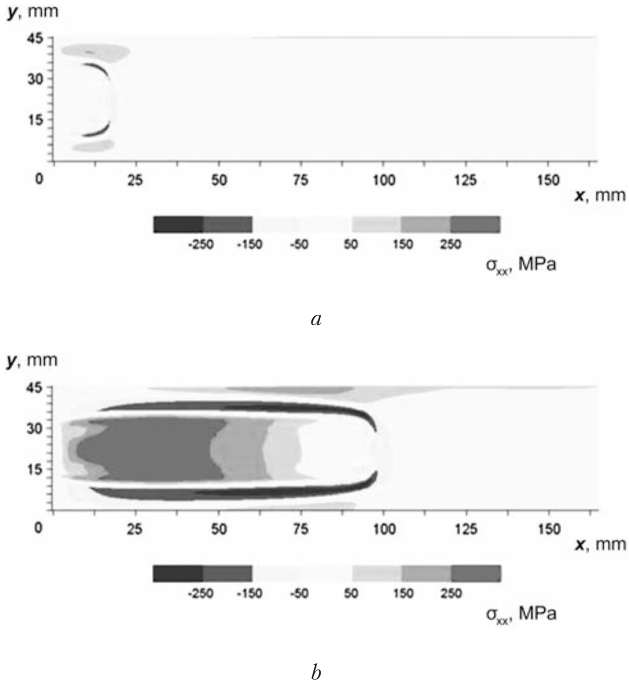


Fig. 9. Distribution of longitudinal stresses in the welded sample: *a* — at initial welding stage; *b* — in stationary thermal regime taking into account the preliminary uniform heating

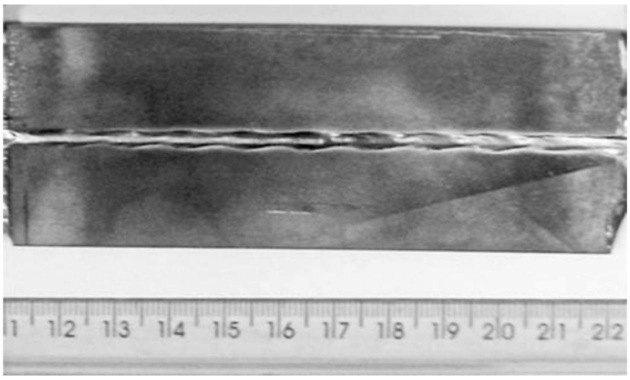


Fig. 10. Defect-free 3 mm thickness alloy plate welded with uniform preliminary heating of the structure with controlled cooling-down after welding

5. The complex of investigations in respect of influence of welding process, as well as preliminary and after-welding thermal processing, on distribution of temporary and residual stresses in various thickness plates is carried out.

It is shown, that under preliminary heating the degree of beam focusing exerts considerable influence on value of tensile axial stresses at periphery of the item during the welding. The temperature measurement under preliminary heating was carried out onto lower surface of plates. The heating up to required temperature was under greater heat input for 10 mm thickness plates, whereas for 3 mm thickness plates the local preliminary heating was characterized with more narrow range of temperatures of intensive heating.

6. It is shown numerically and confirmed experimentally that the use of distributed source for preliminary heating of the item before welding permits to realize the favorable conditions of thermal deforming during the welding and under subsequent cooling-down from the point of view of minimization of metal susceptibility to the macroscopic cold cracks nucleation.

7. It is ascertained, that reduction of temporary tensile stresses at periphery of welded joints of samples, where cold cracks at heating stage are nucleate, results in absence of defects formation, as well as in reduction of negative effect of temperature local peaks owing to movement of concentrated source along welded joint during the preliminary heating

Nomenclature

C — volumetric heat capacity, $J{\cdot}m^{-3}{\cdot}K^{-1}$
I — electric current, A
K — coefficient
E — Young modulus, Pa, GPa
n — surface normal
T — temperature, °C
q — heat flux, W
t — time, s, min.
U — electrical voltage, V
v — velocity, $mm{\cdot}s^{-1}$, $m{\cdot}s^{-1}$
x, y — coordinates, mm, m

Greek Symbols

α_T — surface heat emission coefficient, $W{\cdot}m^{-2}{\cdot}K^{-1}$
λ — metal heat conductivity, $W{\cdot}m^{-1}{\cdot}K^{-1}$
ε_0 — emissivity factor
ε — strain tensor
σ — stress tensor
δ — thickness, mm
τ — shearing stresses, MPa
σ_i — stress intensity, MPa
σ_m — membrane stress, MPa
$\sigma_т$ — material yield stress, MPa
σ_{SB} — Stefan-Boltzmann constant, $5{,}670367{\cdot}10^{-8}$ $W{\cdot}m^{-2}{\cdot}K^{-4}$
υ — Poisson ratio
η — efficiency of heating source
Ψ — material state function

Subscriptsand/Superscripts

ph — preheating
weld — welding

Abbreviations

HAZ — Heat Affected Zone
EWB — Electron-Beam Welding
SSS — Stress-Strain State

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ПРОГНОЗИРОВАНИЕ СКЛОННОСТИ СВАРНЫХ СОЕДИНЕНИЙ СПЛАВА НА ОСНОВЕ γ-АЛЮМИНИДА ТИТАНА К ХОЛОДНОМУ РАСТРЕСКИВАНИЮ ПРИ ЭЛЕКТРОННОЛУЧЕВОЙ СВАРКЕ

Проведено численное моделирование склонности пластин различной толщины сплава на основе -алюминида титана к холодному растрескиванию при электронно-лучевой сварке встык. Обнаружено, что зарождение холодных трещин при сварке может происходить как на стадии охлаждения в результате высоких напряжений в области шва и зоны термического влияния, так и на стадии нагрева, когда на периферии сварной конструкции формируется поле растягивающих уравновешивающих напряжений.

Показано и экспериментально подтверждено, что равномерный подогрев перед сваркой и контролируемое остывание сварного образца позволяет получать бездефектные соединения пластин различных толщин. [dx.doi.org/10.29010/88.9]

Ключевые слова: γ-алюминид титана; электронно-лучевая сварка; напряжённо-деформированное состояние; холодные трещины; контролируемое остывание.

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