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INVESTIGATION OF STRESS-STRAIN STATE OF WELDED JOINTS OF THE SYSTEM TiAl INTERMETALLICS*

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In the work, stress state of welded joints of intermetallic of the TiAl system was investigated. The influence of stress state of weld on cold cracks formation was determined. A mathematical model was created and computational experiments were carried out to determine residual welding stresses in welded joint. Using the methods of optical and electron microscopy, the structure of welded joints of intermetallic of titanium-aluminum system was studied. At the same time, the relationship between the cooling rate of the material after the end of welding process and the structure of welded joint was established. Based on the results of numerical experiments and metallographic examinations, a technology for welding of intermetallic alloy with a subsequent local heat treatment was developed, which allows producing defect-free welded joints. 7 Ref., 4 Figures.

Keywords: *intermetallic, electron beam welding, stresses, cold cracks, local heat treatment*

Intermetallic alloys of the system TiAl are considered to be promising materials in the production of aircraft engine turbines and other products of aerospace engineering, as well as for automotive industry and power generating turbines in heat power plants. They are distinguished by a high strength, heat resistance, creep and corrosion resistance at high temperatures. However, with all mentioned advantages, they are characterized by a low ductility at room temperatures, which leads to significant difficulties in producing different semi-finished products. Therefore, the successful production of TiAl system alloys depends on achieving a suitable combination of ductility at a room temperature, strength, fatigue strength, creep, fracture toughness, as well as oxidation and corrosion resistance. The required mechanical properties are closely related to such factors as chemical composition, microstructure and technology of treatment. One of the ways to increase ductility is alloying with elements that can influence the formation of the structure during cooling of the alloy [1]. The industrial implementation of these alloys also depends on the development of technology for their joining. From intermetallics, a wide range of products can be manufactured, a part of which are welded assemblies; therefore, the development of technology for welding intermetallics of the system TiAl is very relevant [2].

Electron beam welding (EBW) is one of the most promising methods for producing welded joints of the mentioned materials [3]. In the process of producing welded joints of TiAl system intermetallics, their essential defect is cold cracks in the welds, which occur at the temperatures below 700 °C, when the material passes from a viscous to a brittle state. The brittleness of a weld in the state after welding, in its turn, is determined by its structure and, at the increment of welding stresses during cooling, leads to the appearance of defects such as cold cracks, the source of which are microcracks, dislocations, etc.

The aim of this work was to study the stress-strain state of welded joints of TiAl system intermetallics and to develop the technology of welding that allows producing defect-free welded joints.

To calculate the value of welding stresses, it is necessary to take into account the thermal effect on the metal being welded, which is determined by heat input during welding. The most important characteristic of heat input is the fact, that it determines the rate of cooling the metal and, therefore, affects the microstructure of weld and heat-affected zone. Since EBW proceeds at a high energy concentration, the formed HAZ has insignificant sizes of 1 mm [4].

Welding of specimens of intermetallic alloy of the TiAl system (Ti–44Al–5Nb–3Cr–1.5Zr) with a size of

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30×100 mm and a thickness of 3 mm was carried out at a heat input of 2500 J/cm.

The TiAl system intermetallic welds produced by EBW at the specified heat input of welding had transverse cold through cracks passing through the weld into the heat-affected zone and the base material.

The initiation of cold cracks during welding occurs at the cooling stage as a result of growing stresses. To calculate the stress state, a mathematical model was created, on the basis of which computational experiments were carried out.

For welded plates with a thickness of 3 mm, EBW proceeds in the mode of key hole penetration. Therefore, the temperature field can be considered uniform across the thickness [5]. The kinetics of temperatures can be described using the following non-stationary heat conductivity equation:

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

where $c\gamma$, λ are temperature-dependent volumetric heat capacity and thermal conductivity of metal, respectively; T is the temperature of the structure at the moment of time t at the point with coordinates (x, y); α_T is the coefficient of surface heat transfer to the rigging (bench support); ε_0 is the degree of blackness of plates surface; σ_{SB} is the Stefan–Boltzmann constant; T_0 is the ambient temperature); q is the heat flux from the source of welding heating in the considered area of the surface, which in the case of key hole penetration in EBW can be described as

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

where η is the efficiency of the source of welding heating; U is the accelerating voltage on the electron beam gun; I is the welding current; K_S is the coefficient of energy flux concentration in the electron beam.

The boundary conditions for the thermal conductivity equation (1) for the considered case of EBW in vacuum have the following form:

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

where n is the normal to the surface of the structure.

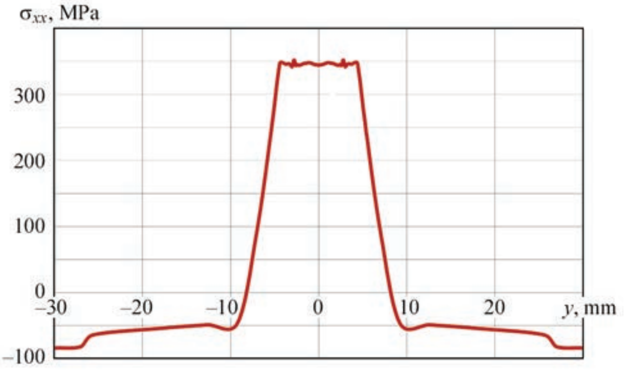

Figure 1. Distribution of longitudinal stresses along the weld length (unsupported welding)

Figure 1 shows the distribution of residual welding stresses along the length of the plates produced using a computational experiment.

The highest level of residual stresses — 330 MPa is observed in the center of the weld, which is also confirmed by the data obtained by the method of X-ray diffraction analysis — 335 MPa. On the base material, the stresses transfer from tensile into compressive. The welding stresses arising during cooling of the specimen in combination with the brittle structure of the weld metal, lead, in its turn, to the appearance of such defects as cold cracks.

Metallographic examinations of the structure and fracture surface in the weld are shown in Figure 2. The microstructure of the weld in Figure 2, *a* consists of γ-TiAL and α_2-TI_3Al-phases. The weld has a hardness of 5100–5300 MPa. According to fractographic investigations (Figure 2, *b*), it is seen that destruction of welded specimens is observed in the elastic region by a transcrystalline fracture. On the fracture surface, sections with different structures are observed. In the weld metal, the propagation of the main crack proceeded stepwise.

The mentioned structure has a low ductility. At a high cooling rate of the weld metal — 500 °C/s, the conditions for forming metastable phases are created, which increase the tendency of the metal to cold cracking. A large role in the formation of cracks is played by residual welding stresses and, especially, by their growth during cooling as a result of a high temperature gradient. In order to prevent cold cracks, it is necessary to provide a delayed cooling rate with a decrease in the temperature gradient and, accordingly, in the level of stress state [6]. Reducing the stress state is an important factor for prevention of the cold cracking. For this purpose it is necessary to conduct heat treatment of welded joints.

In view of the fact that cracks are formed immediately after welding, there is no possibility to perform heat treatment in a stationary furnace. The most

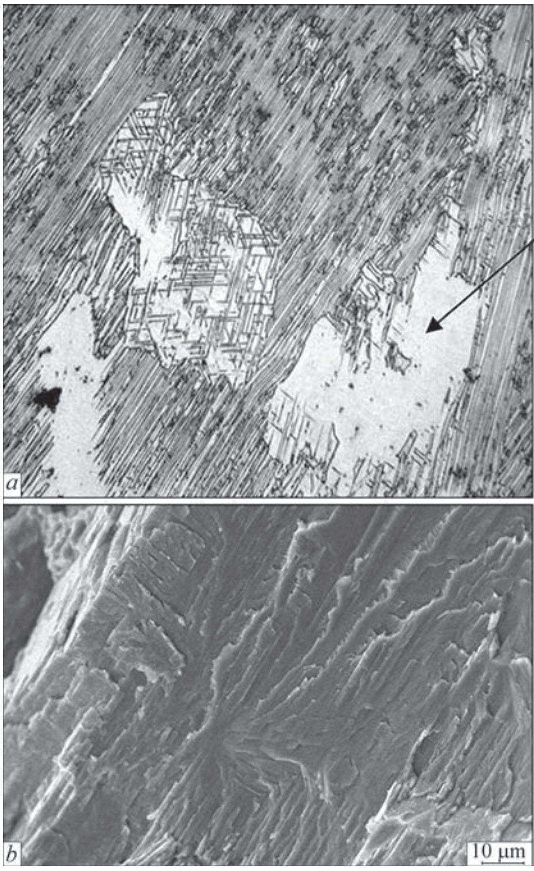

Figure 2. Microstructure of weld metal (*a*) and fracture surface of the weld (*b*) produced by EBW

rational is local heat treatment (LHT) with an electron beam. We developed LHT of welded joints of the TiAl system intermetallic with an adjustable cooling rate. This process is carried out as follows: immediately after welding, the electron beam is directed to the middle of the weld and with the help of a special computer program it is deployed to the desired configuration in one and the other direction from the middle to the end of the weld. In this case, the beam remains stationary, and the welding current is reduced by 1/3.

Due to a decrease in the welding current, the heat input in the LHT process decreases to 1700 J/cm, which is 1.5 times lower as compared to the same value during welding.

The period of the mentioned heat treatment is 5 minutes. At the same time, the investigations showed that the temperature of the welded joint is maintained up to 950 °C. The cooling rate in this case is reduced to 30 °C/s. In this regard, the temperature gradient decreases and, accordingly, the welding residual stresses are reduced to 260 MPa. In this case, cold cracks in the welds are practically not formed. Figure 3 shows the stress state of the weld after LHT.

The developed technological scheme of EBW and heat treatment allows reducing the level of residual welding stresses by more than 25 %.

Metallographic examinations of the welded joint produced by EBW with the following LHT (Figure 4, *a*) showed that the weld metal has a three-component structure: matrix of the γ-TiAl phase, colonies of (γ-TiAl + α_2-Ti_3Al)-phases and precipitations of residual β_0(B2)-phase along the boundaries of the colonies. The hardness of the weld metal is 4400–4500 MPa. It was shown [7] that such a structure slightly increases ductility and in combination with the stresses, which are lower than in the initial state, it improves crack resistance of the intermetallic weld.

Examinations of fractures of the specimens produced by the proposed scheme EBW + LHT showed that the fracture occurs according to the intercrystal-

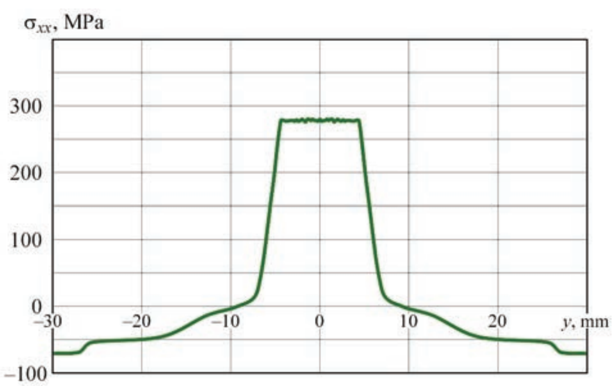

Figure 3. Distribution of longitudinal stresses along the weld length after LHT

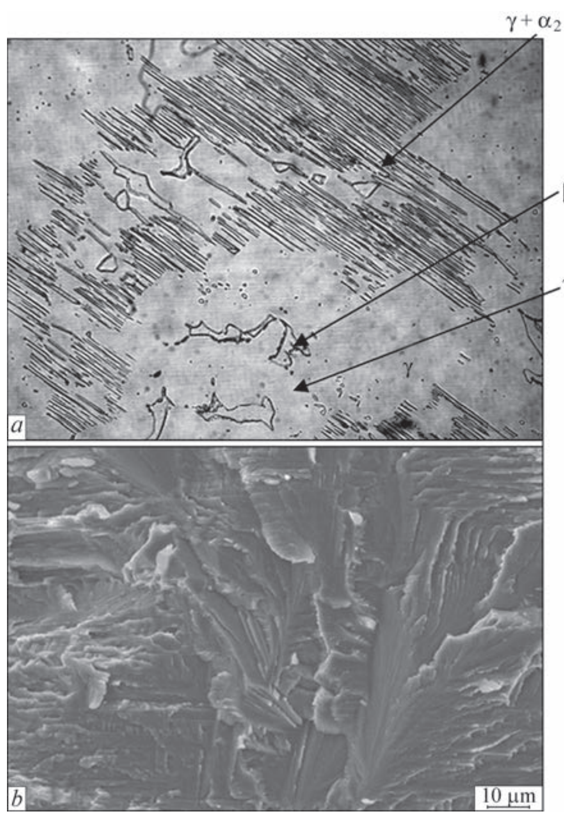

Figure 4. Microstructure (×200) of weld metal (*a*) and fracture surface structure (*b*) produced by EBW with the following heat treatment

line mechanism. Figure 4, *b* shows fractography of the weld. The fracture of the weld metal is intercrystalline. Crushing of the γ-phase is observed due to dispersed precipitations of the α_2-phase. On the surface of facet fracture, the spalling facets are separated by tearing regions. That fact is predetermined by plastic shear and is a sign of ductility of the material. It can be assumed that the material resists fracture to some extent and has some ductility.

Comparing Figures 2 and 4, it can also be noted that a high heat input during welding provides coarser grain structure of weld metal as compared to heat treatment at a lower heat input.

Thus, as a result of reduction of heat input, the developed modes of local heat treatment allow slowing down the cooling rate of the weld and, thereby, creating favorable structural changes, as well as significantly reducing stress state of welded joints and practically avoiding the formation of cold cracks.

Conclusions

A mathematical model was developed and computational experiments were carried out, which allowed calculating the stress state of the intermetallic weld in the initial state after welding and LHT.

The cooling rate during application of heat treatment is 30 °C as compared to the cooling rate immediately after welding — 500 °C.

A 1.5 times decrease in heat input slows down the cooling rate of the weld, which contributes to the formation of a three-component structure: matrix of the γ-TiAl phase, colonies of (γ-TiAl + α_2-Ti_3Al)-phases and precipitations of residual β_0(B2)-phase along the boundaries of the colonies, which allows increasing the ductility of the weld.

During the use of heat treatment, the temperature gradient decreases and, accordingly, the welding voltages decrease by more than 25 %.

It is shown that the use of LHT can significantly improve the structure of weld metal, reduce the value of residual welding stresses, and thereby increase the crack resistance of the weld.

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