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EFFECT OF LOCAL HEAT TREATMENT ON MECHANICAL PROPERTIES OF WELDED JOINTS OF INTERMETALLIC OF TiAl SYSTEM PRODUCED BY ELECTRON BEAM WELDING

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Welded joints of intermetallic β-stabilized alloy TiAl–Ti–44Al–5Nb–3Cr–1.5Zr (at.%) were investigated. Intermetallic billets of 3 and 10 mm thickness were welded by electron beam welding. In order to prevent arising of cold cracks in welded joints of titanium aluminide specimens of different thickness, the following postweld local heat treatment using an electron beam was performed. The mentioned method of treatment is one of the most attractive to improve the structure of ingot and reduce the level of residual welding stresses, which, in its turn, significantly increases mechanical properties of the alloy. Static tensile tests were performed to evaluate the strength of welded joints. The specimens fractured throughout the base material. The paper presents histograms showing the values of tensile strength (σ_t) of welded joints produced during tensile tests for the specimens of different thickness with and without the use of local heat treatment (LHT). It is shown that the use of local heat treatment increases tensile strength of the specimens of 3 and 10 mm thickness, as compared to the specimens produced without LHT. In addition, the values of this index for welded joints of different thicknesses, which are produced using this technique, are quite uniform. Comparative analysis of the results of tensile tests and the results of microhardness studies was performed, which showed that fracture of the specimens took place in the zone of lowering mechanical properties. The nature of fractures of different parts of welded joint was studied, which confirmed that fracture occurs in the zone of brittle part of the specimen. It is known that mechanical properties of welded joint are closely related to its structural state. During local heat treatment, an additional β_0 (B2) phase appears in the structure, which increases the ductility of the weld material, 14 Ref., 2 Tables, 9 Figures.

Keywords: intermetallic alloy of TiAl system, electron beam welding, local heat treatment, mechanical tensile tests, tensile strength, structural state, microhardness

Intermetallics are used to manufacture a wide range of products for aircrafts. In the manufacture of a number of assemblies of high and low pressure turbines, it is advisable to use welding [1].

One of the most important problems of modern metals science is to increase the level of mechanical properties of titanium alloys, as well as welded joints and assemblies, which are now widely used for manufacture of parts of gas turbine engine (GTE).

Thus, optimization of properties and development of technologies for welding structural intermetallic of the titanium-aluminium system for the further use is quite relevant.

One of the most suitable ways to produce high-quality intermetallic joint is electron beam welding (EBW), which allows welding products of different geometric shapes, producing welds of different length, as well as intermittent welds. As compared to other types of fusion welding, electron beam welding also has advantages: first, because it is carried out in a high vacuum, it provides a protection of such active material as titanium; secondly, during EBW a narrow weld and a very negligible heat-affected zone are formed that, in turn, should lead to minimum deformations of a welded joint [2, 3].

While producing welded joints of intermetallics of TiAl system applying EBW method, their significant defect is cold cracks, arising at the temperatures below 700 °C, when the material changes from tough to brittle state [4, 5]. A low ductility of welded joint at the state after welding, in turn, is determined by the unfavourable structure of welded joint and, with an increase in welding stresses during cooling, it leads to the appearance of cold cracks [6–8].

In order to struggle cracks, it is necessary to provide a slow cooling rate [9]. At the same time the temperature gradient and, accordingly, the level of stressed state are reduced, which is an important factor in struggling crack formation. At the same time, the ductility of welded joint is improved as a result of favourable structural transformations.

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The most important task of increasing reliability of aircraft and gas turbine engines is to prevent danger of fracture of the most critical structural elements. The rigidity of the requirements to the serviceability of welded structures of critical purpose, manufactured based on titanium alloys, can be satisfied by a high quality of welded joints. The challenging direction of investigation is to increase the mechanical properties of welded joint to the level not lower than the properties of the initial material by preventing the formation of macro- and microcracks, porosity in the weld and near-weld zone.

Electron beam welding with the subsequent local heat treatment. Experiments on EBW and investigations of welded joints of intermetallic alloy Ti–44A1–5Nb–3Cr–1.5Zr (at.%) were carried out on the specimens with a thickness of 3 and 10 mm. The thickness of the specimens for testing welding modes was chosen based on the fact that thicknesses δ = 3 mm can be used in welded assemblies of GTE of high and low pressure, and the choice of 10 mm was justified by the fact that such thicknesses are used for compressor blades of aircraft engines.

The specimens were welded with preheating on the following mode: $T_{\text{preheat}} = 450$ °C; $U_{\text{acc}} = 60$ kV; $V_{\text{w}} = 7$ mm/s; $P = 5\cdot10^{-3}$; $I_{\text{b}} = 35$ mA (for a thickness δ = 3 mm) and $I_{\text{b}} = 90$ mA (for a thickness δ = 10 mm). The produced specimens had transverse cracks that passed through the weld.

With the help of calculation methods, the thermal conditions were determined which lead to the formation of cold cracks. Investigations of the stress state of welded joints, as well as the processes of structure formation occurring in EBW were carried out. As a result of generalization of these investigations, it was shown that in addition to preheating, local heat treatment (LHT) should be performed immediately after welding. For this purpose, the most rational is the use of capabilities of the electron beam. Local heat treatment by scanning the beam along the weld immediately after welding will reduce the rate of increase of temporary stresses during welding and the level of residual welding stresses, which will reduce the probability of crack formation.

Technology of EBW of intermetallic Ti–44Al–5Nb–3Cr–1.5Zr (at.%) with the subsequent LHT, which occurs right after the completion of welding process, was developed, providing the rate of cooling welded joint in the range of 0.7–0.9 °C/s. The electron beam is defocused from 2 mm in welding with a diameter of up to 15 mm during heat treatment, and the welding current is reduced by 1/3, which allows maintaining the level of temperature of welded joint at 1000 °C during 5 min. The application of the proposed LHT method allowed reducing the level of residual welding stresses and, due to that, avoiding the formation of cracks in the weld on the material with a thickness of 10 mm [10].

For the plates with a thickness of 3 mm, the modes of controlled cooling were proposed that allow compensating for excessive surface heat transfer. Using this technology, it is recommended to carry out heat treatment with a defocused and deployed electron beam with a gradual decrease in its power and, namely, immediately after the completion of welding, the electron gun should be placed in the middle of the weld and the beam should be deployed to the desired configuration on one and the other side from the middle of the weld to its end with the use of a special computer program. The scanning frequency of the electron beam is 100 Hz, and the welding current is reduced by 1/3. The total time of the specified heat treatment is 10 min. The temperature of the welded joint of 1000 °C is maintained during 5 min. Then, due to a slow (~ 5 min) reduction in current according to a special program, the welded joint is cooled to a temperature of 500 °C [11].

The use of local heat treatment allowed reducing the welding residual stresses by almost 30% - from 225 to 160 MPa. This made it possible to avoid the appearance of cold cracks and produce defect-free joints.

Investigation of mechanical properties of welded joints. To evaluate the strength of welded joints, static tensile tests were performed. The tests were

Figure 1. Appearance of intermetallic specimen, made for mechanical tests: *a* — thickness 3; *b* — 10 mm

Figure 2. Intermetallic specimens after tensile test: *a* — thickness 3; *b* — 10 mm

performed according to GOST 1497–84 in the rupture machine ZD-4.

To carry out tests, the specimens MI-12 were prepared.

Figure 1 shows the appearance of the specimens manufactured for tensile tests.

Fracture of the specimens occurred on the base material.

Figure 2 shows the specimens of intermetallic of a cylindrical shape after tensile tests.

Figure 3 shows a typical tensile diagram of a welded joint of intermetallic of 3 and 10 mm thickness, produced by EBW with LHT.

The results of mechanical tests of welded joints of the specimens produced during tensile tests are given in Table 1.

Table 1. Tensile strength of welded joints

Specimen number	Thickness δ, mm	Value σ_t MPa	Place of fracture
1	3	310.9	BM
2	3	319.1	Same
3	10	343.8	»
4	10	337.4	»
5	10	346.6	»
Average value: δ = 3 mm δ = 10 mm		315.0 342.6	

Table 2. Tensile strength of welded joints of intermetallic, produced by EBW method without LHT

Specimen number	Thickness δ, mm	Value σ_t MPa	Place of fracture
1	3	197.8	BM
2	3	152.1	Same
3	3	175.5	»
Average value		175.13	

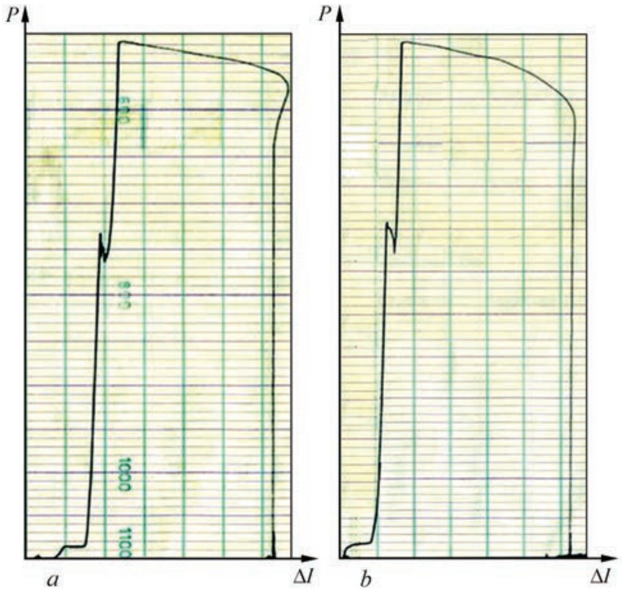

Figure 3. Diagram of tensile tests of welded joints: *a* — thickness 3; *b* — 10 mm

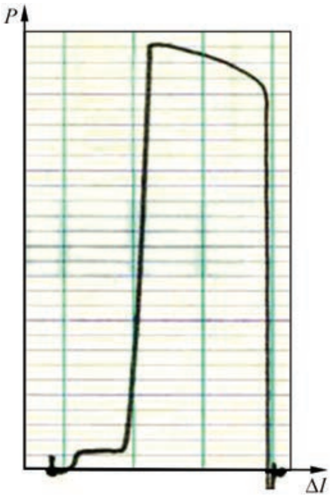

Figure 4. Diagram of tensile tests of 3 mm thick welded joints produced by EBW method without LHT

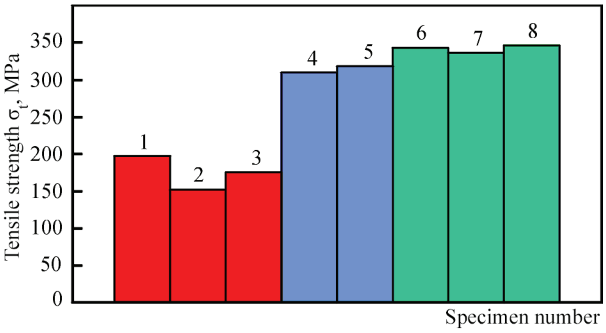

Figure 5. Value of tensile strength of welded joints of intermetallic produced during tensile test: 1–3 — produced by EBW without LHT (δ = 3 mm); 4, 5 — produced by EBW with the subsequent LHT (δ = 3 mm); 6–8 — produced by EBW with the subsequent LHT (δ = 10 mm)

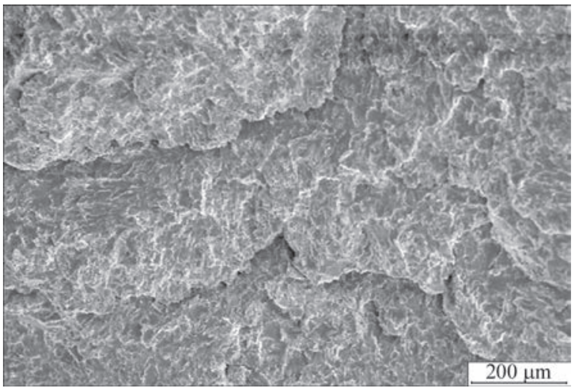

Figure 6. Fractogram of fracture surface of initial metal of titanium intermetallic of TiAl system using LHT

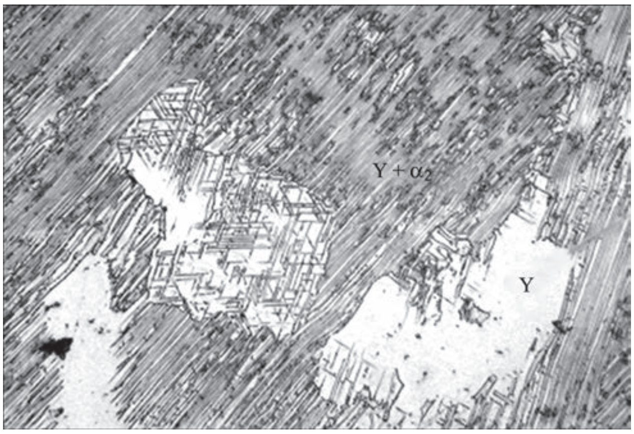

Figure 8. Microstructure (×500) of weld, produced without LHT

For comparison, mechanical tests of welded joints of the specimens produced by EBW without LHT were performed. Table 2 shows the results of tests.

Figure 4 shows a typical tensile diagram of 3 mm thick welded joint of the intermetallic produced by EBW without LHT.

Figure 5 shows histograms with the values of tensile strength (σ_t) of welded joints, produced during tensile tests for the specimens of different thickness with and without LHT.

As is seen from the histograms, the values of tensile strength of the specimens with a thickness of 3 and 10 mm, welded using postweld local heat treatment, is much higher than for the specimens produced without LHT and is sufficiently uniform for the specimens of different thicknesses.

Measurements of microhardness of welded joints showed that in the area of the base metal a decrease in microhardness to 3570 MPa occurs as compared to the weld having a microhardness of about 5430 and HAZ, which has a microhardness of 4810 MPa.

Thus, the results of measurements of microhardness of welded specimens correlate with the results of strength of the welded joint after the fracture of all specimens — the fracture of the specimens occurred approximately in the zone of reduction of mechanical properties.

The nature of fractures of different parts of the welded joint was studied. Figure 6 shows a fractogram of the fracture surface of the welded joint in the area of the base material. It is seen that step fracture is observed in the areas of the base material. The steps move in a one direction parallel to each other. This type of fracture is characteristic of brittle fracture.

The fractures of welded joints of titanium aluminide, which were welded using postweld LHT, have a mixed nature of fracture (with ~ 30 % of a tough component).

Fractographic examinations (Figure 7) confirmed that fracture occurs in the area of a brittle part of the specimen.

Analysis of the data obtained during the test showed that the specimens welded with the subsequent LHT have the highest values of tensile strength.

The fracture not along the welded joint is always treated as a sign of a high quality of welding [12–14].

Since mechanical properties of the welded joint are closely related to its structural state, it is necessary to conduct a comparative analysis of metallograph-

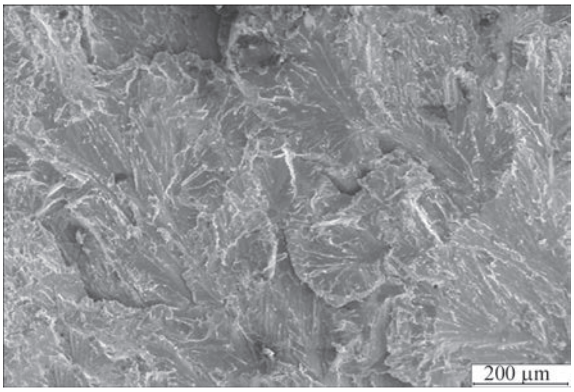

Figure 7. Fractogram of fracture surface of initial metal of titanium intermetallic of TiAl system, area of weld metal (×200)

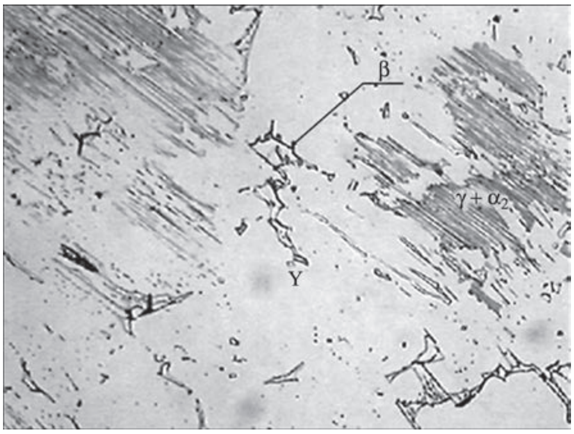

Figure 9. Microstructure (×500) of area of base metal of welded joint of titanium aluminide, produced by EBW with the subsequent LHT

ic examinations with mechanical characteristics. The weld produced by EBW without a further heat treatment has a two-component structure consisting of γ and α_2-phases (Figure 8), and the use of LHT facilitates a reduction in the cooling rate of the weld and the formation of β-phase (Figure 9), which is responsible for increase in the ductility and strength of the welded joint.

This structural difference of welded joints, produced with the subsequent postweld heat treatment, has a positive effect on the level of strength during mechanical tests and, namely, allows increasing the tensile strength of the welded joint on average by about 1.8 times — from 175 to 315 MPa.

Thus, the LHT of the welded joint allows a significant improvement of its quality.

Conclusions

1. Mechanical tensile tests of welded joints showed that fracture of the specimens occurs on the base material. This indicates a high quality of welding.

2. Comparative analysis of the level of strength of welded joints with the results of microhardness measurements, as well as with the results of fractographic examinations showed that fracture of the specimens occurred in the zone of reduction of mechanical properties.

3. With the use of LHT of welded joints during cooling from the temperature of 1000 °C, a phase transformation occurs, during which an additional β_0 (B2) phase appears in the structure, which is located along the colony boundaries and facilitates an increase in the ductility of the material.

4. The use of LHT increases the level of strength of the welded joint by approximately 1.8 times.

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