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ELECTRON BEAM WELDING OF SHEET INTERMETALLIC ALLOY WITH A CONTROLLED COOLING RATE

E.L. Vrzhyzhevskyi, N.V. Piskun, O.A. Velykoivanenko, I.I. Statkevych, T.G. Taranova

E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine

ABSTRACT

The objective of this study is development and testing of elements of the technological process of electron beam welding (EBW) of intermetallic alloys of TiAl system, which allows performance of welding, preheating and subsequent local heat treatment of welded joints in one pass in one chamber, that enables preventing defects of the type of cold cracks, due to a controlled cooling rate. The work explains why EBW is exactly the most suitable process for welding titanium-based intermetallic alloys. A welding method is proposed and described in detail, which is performed in the gravity position at cantilever fastening of the samples in a special device, while heat treatment is conducted immediately after completion of the welding process, ensuring an optimal cooling rate of the welded joint. It is found that cold cracking in the intermetallic welded joints is related to a low ductility of as-welded material. A mathematical model was developed for numerical prediction of the temperature field kinetics and stressed state calculation. The model was used as a basis to conduct a computational experiment and to determine the thermal conditions leading to cracking in EBW process. It is shown that the highest level of residual stresses is formed directly after completion of the welding process; it is equal to 350 MPa and is observed in the weld center. In order to prevent cold cracks in welded joints of titanium aluminide samples, a technological measure was proposed, which combines EBW of Ti–44Al–5Nb–3Cr–1.5Zr (at.%) intermetallic with preheating and postweld local heat treatment (LHT). It was numerically shown and experimentally confirmed that application of a distributed source of sample preheating before welding allows creating favorable conditions during welding and at further cooling, namely lowering the tensile stresses. The way the process is implemented and its influence on the stressed state and structure of the produced joints are described in detail. The work gives the modes of EBW of sheet intermetallic alloy with a controlled cooling rate and results of structural and mechanical studies of the welded joints, produced by the proposed technology.

KEYWORDS: electron beam welding, TiAl system intermetallics, sheet plates, controlled cooling rate, stressed state, “gravity” welding, local heat treatment

INTRODUCTION. RELEVANCE

Literature review showed that the intermetallic alloys of TiAl system have been ever wider applied recently in manufacture of parts and components of gas turbine aircraft engines, as well as in other industries.

At this stage of welding technology development the question of sheet metal welding is of considerable importance. Use of thin materials in various structures enables lowering the weight and overall dimensions of welded structures, and, thus, reducing their cost, which is particularly noticeable when using titanium-based intermetallics.

Intermetallic alloys of TiAl system [1] have the most unfavourable characteristics for welding in sheet structures. It is associated with low ductility of this material at normal temperature, as well as with considerable chemical activity.

Intermetallic alloys of TiAl system, having low specific weight, high heat resistance, long-term strength and creep in the temperature range of 750–850 °C are finding application in manufacture of parts and components of gas-turbine aircraft engines, as well as in other industries [2].

As this alloy of TiAl system is a promising material for wide application in structures of aircraft engine turbines, automotive parts and in some other sectors [2], it requires joining methods, which allow welding products of diverse geometrical shapes, making welds of different length, as well as intermittent welds. In our opinion, electron beam welding (EBW) is the most promising method to produce intermetallic joints. Compared to other welding methods, it has the following advantages: first, as it is conducted in high vacuum, it completely ensures protection of any active material, which titanium is; secondly, a very narrow weld and a very small HAZ form at EBW, which, in its turn should lead to minimal deformations of the welded joint [3].

However, a significant drawback of these alloys are cold cracks, arising at welded joint cooling at temperatures below 700 °C, when the material goes from the tough into the brittle state [2].

At increase of welding stresses during cooling a low ductility of the welded joint in as-welded state leads to development of defects of the type of cold cracks. In this connection, in order to produce a sound welded joint and avoid cold cracking, it is necessary to lower the temperature gradient and the welding stresses, respectively, which is ensured by a slowed down cooling rate.

Table 1. Chemical composition of experimental alloy

Alloy	Ti	Al	Nb	Cr	Zr
wt.%	52.82	28.8	11.72	3.51	3.16
at.%	45.92	44.54	5.26	2.82	1.46

Modern methods and technologies of welding sheet metal envisage application of heat sinks, different kinds of forming backing [1], or other equipment, which would prevent thin metal burning-through. Such a process is characterized by rather low welding speeds. This, in its turn, has a negative impact on productivity, material costs for production and, eventually, the product cost.

The authors of work [4] use copper backing. Here, it is important to ensure their tight contact with the edges to be welded along the entire length, as in the places where gaps remain between the backing and the edge, the welding process is accompanied by burn-through and sagging of the weld. In welding sheet materials, it is exactly the concentration of the heating source heat which is important, as it is favourable not only for formation of the weld, but also for the HAZ.

Known is a method of controlling the cooling rate of intermetallic welded joints described in work [5], when the sample is welded on a ceramic plate, which slows down the welded joint cooling rate that influences the magnitude of welding stresses. A disadvantage of this method is that the heat conductivity and the cooling rate of the welded joint, respectively, are determined by thermophysical properties of this ceramic backing, the cooling rate being practically not controlled.

Therefore, development and optimization of the technological process, which enables controlling the electron beam due to distribution of power of the electron beam thermal impact, in order to create the specified temperature field at EBW with simultaneous preheating and further heat treatment of the plate being welded, are highly important.

INVESTIGATION MATERIAL AND PROCEDURE

An intermetallic alloy of the following composition Ti–44Al–5Nb–3Cr–1.5Zr at.%, developed and produced at PWI by the method of cold-hearth electron beam melting (Table 1), was studied in the work [6].

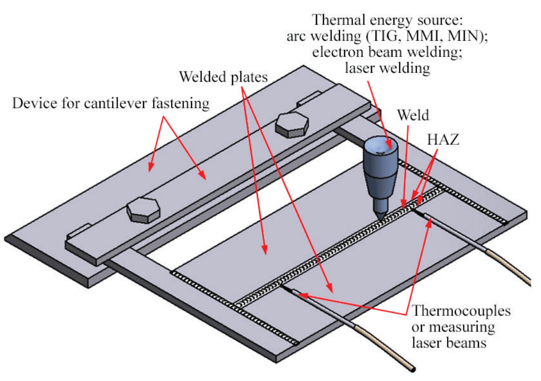

Figure 1. Scheme of performance of EBW process

Electron beam welding of the intermetallic was performed in the welding chamber of UL-144 unit of 2.16 m^3 volume (1200×1200×1500 mm). It has a 60 kW power unit at 60 kV accelerating voltage, and wide adjustment capabilities to implement additional technological processes. The diagram of EBW process is shown in Figure 1.

Manipulator of UL-144 welding chamber was upgraded for welding Ti–44Al–5Nb–3Cr–1.5Zr (at.%) intermetallic. The upgraded sealed lead-in ensures lowering of the resistance at shaft rotation using an oil “wedge”. FL 86STH156-620B step motors with software for gun movement are mounted on the manipulator. Such upgrading allows assigning and reproducing the assigned movement trajectories with 0.1 mm accuracy. Moreover, additional equipment was installed, which provides cantilever fastening of the sample to be welded.

Software support of EBW and local heat treatment was performed using industrial computer Advantech 610.

Samples for investigation were prepared after EBW (Figure 1). Plates of 100x30 mm size 3 mm thick from Ti–44Al–5Nb–3Cr–1.5Zr (at.%) alloy were welded. Before welding the plates were ground from all sides and assembled end-to-end without a gap.

To avoid deplanation of the plates during welding the run-on and run-off tabs from VT1-0 titanium alloy were mounted from two sides and welded across the sample. The length of run-off tabs, which were fastened in a special device, was 160 mm. The weld was started and ended on the run-on and run-off tabs.

The ingot microstructure was revealed through etching in a solution of hydrofluoric and nitric acid (1 part of hydrofluoric (HF) and 3 parts of nitric (HNO_3) acid).

Intermetallic hardness was measured by Leco hardness meter at 25 g load.

Fractographic studies were conducted in scanning electron microscope JSM-840 of JEOL, Japan, which is fitted with microanalyzer of Link system 860/500 (Great Britain).

As cracking occurs not only at the cooling stage, but also at the stage of metal heating before the start of the welding process, it is necessary to create a technology, which allows producing defectfree welded joints. Experiments on welding and investigation of welded joints of intermetallic alloy Ti–44Al–5Nb–3Cr–1.5Zr (at.%) were conducted on 3 mm sheet samples. Sample thickness for optimization of the welding modes was selected proceeding from the fact that 3 mm thicknesses can be used for blades of high and low pressure turbines.

EBW was conducted without preheating by the scheme shown in Figure 1 in the following mode:

$$U_{acc} = 60 \text{ kV}; I_b = 35 \text{ mA}; V_w = 7 \text{ mm/s};$$
$$P = 5\cdot10^{-3} \text{ Pa}.$$

After welding the weld was cooled to room temperature in the chamber.

In order to ensure a uniform cooling of the material, welding is performed with the sample in unrestrained position (gravity welding) [7]. Welding and heat treatment are conducted with cantilever fastening of the samples in a special device. Heat treatment is performed immediately after completion of the welding process, ensuring a cooling rate of not more than 70 °C/s. Such a method allows determination of the shape of the temperature field in welding of any joints of various metals, a characteristic feature of which is that the temperature fields are determined under the conditions of cantilever fastening without the possibility of heat removal through mechanical contact.

Formation of the weld in “gravity’ position is particularly important, as it allows avoiding a considerable number of problems associated exactly with welding sheet materials. Better results are achieved in welding of a butt joint with the sample in unrestrained position without application of forming devices or backing, as here a two-sided exit of gases and metal vapours from the penetration channel is ensured, when gas evolution is facilitated [8].

INVESTIGATION RESULTS

Visual investigation of the welded butt joints showed that transverse cold cracks (Figure 2, *a*) are observed in the weld, which pass through the welded joint and end in the base material on both sides of the sample. As mentioned above, the main source of crack initiation is the low ductility of the material at room temperatures (ductile-brittle transition temperature is 700 °C) and impossibility of resisting crack initiation, as a result of welding stress formation.

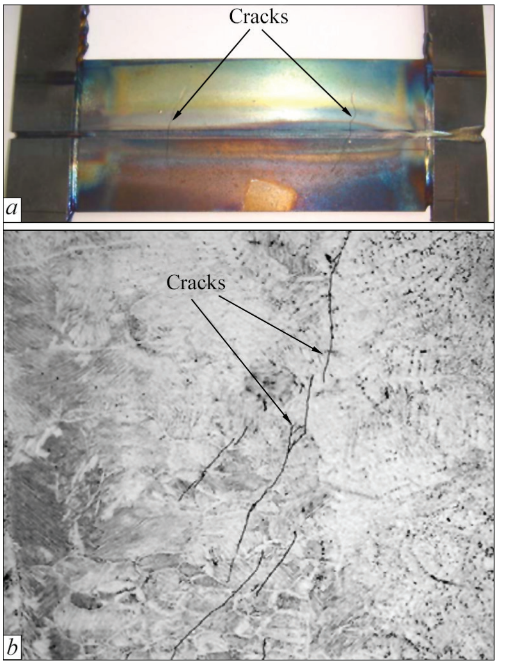

Figure 2. Sample of EB welded joint of intermetallic alloy of Ti–44Al–5Nb–3Cr–1.5Zr, at.% system: *a* — general view; *b* — microstructure (×200) of weld metal [8]

When studying the microstructure of the weld zone, an inhomogeneity of the weld metal structure in the form of $(\gamma+\alpha_2)$-phase colonies is observed. They are located along the fusion zone and have the microhardness of 5110–5270 MPa. Numerous cracks of 100 to 300 μm length, located parallel to the fusion line, were also found in this region (Figure 2, *b*) [9].

Fractographic studies showed that the main crack developed in steps in the weld metal (Figure 3, *a*). A change in the structure from the face to the reverse side of the weld is observed. In the face side region the structure is fine-grained (Figure 3, *a*), and in the metal of the weld reverse side the structure consists of elongated lamellas (Figure 3, *b*). Weld metal fracture is intergranular with small secondary cracks. One can see a γ-phase fragmentation (Figure 3, *b*) due to dispersed α_2-phase precipitates. Sections where no γ-phase fragmentation occurred were also found on the fracture surface.

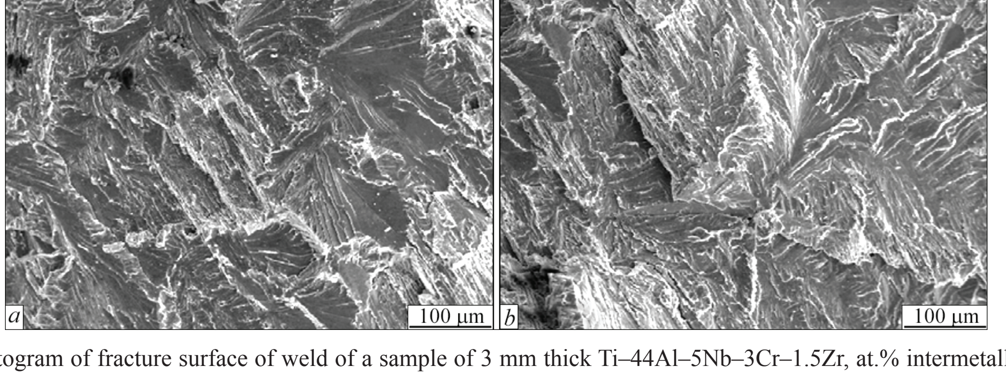

Figure 3. Fractogram of fracture surface of weld of a sample of 3 mm thick Ti–44Al–5Nb–3Cr–1.5Zr, at.% intermetallic alloy: *a* — weld structure (face side), ×200; *b* — fracture area with elongated lamellas on the reverse side, ×200

As shown by experience of previous researchers, residual stresses form in welded joints at EBW, which in combination with the structure lead to cracking in the weld.

Proceeding from the above, further research consisted in development of EBW technology, which will ensure a lowering of the level of residual welding stresses, and will improve weld ductility, which will allow avoiding cold cracking.

INVESTIGATIONS OF THERMAL CONDITIONS, UNDER WHICH DEFECTS FORM IN WELDED JOINTS

A numerical experiment was used to determine the thermal conditions, under which stresses arise in 3 mm samples, leading to cracking [10].

Temperature field kinetics was considered at sample preheating, welding and further cooling to room temperature. The kinetics of the sample stress-strain state (SSS) was predicted proceeding from these numerical results. At initiation of cold cracks, a higher level of tensile welding stresses is the determinant factor.

Given below are the calculated graphs of residual longitudinal stress distribution in the cross-section of the welded joint along the length of a 3 mm plate, which were derived in a computational experiment (Figure 4, *a*). Investigations of the stressed state of the welded joints showed that in as-welded state tensile stresses form in the weld center and in the fusion zone, the level of which changes from 350 to 370 MPa. Longitudinal tensile stresses acting along the weld are nonuniform. This is on average 5 % higher than the transverse stresses in some regions (Figure 4, *b*). With greater distance from the weld center, the level of residual stresses becomes lower and at 7 mm distance from the center (in the base metal) the stresses become smaller at approximately 100 MPa, and then they gradually decrease to 0 and at the plate ends they change from tensile into the compressive ones.

Thus, cold crack initiation in welding occurs both at the cooling and at the heating stage, as a result of high stresses in the area of the weld and the fusion zone, where the tensile stress field is formed.

The nature of distribution of residual longitudinal stresses in the cross-section of a welded joint produced using a computational experiment, is shown in Figure 4, *b*. One can see that residual longitudinal stresses are nonuniformly distributed in the cross-section across the width. Tensile stresses act in the weld and zone adjacent to it and compressive stresses are present in the other part of the cross-section.

The highest level of dangerous residual tensile stresses forms in the center of the weld and HAZ, and it is equal to 350 MPa, which is also confirmed by the data obtained by X-ray structural analysis — 315 MPa. These stresses change from tensile into compressive ones in the base material. It is known that the stress magnitude is influenced by the chemical and phase composition of the welding consumables.

A factor which determines the process of residual stress formation in welding is the temperature field at the stable stage of the process in the plates being welded. Nonuniform heating of the welded joint in welding results in development of residual plastic shrinkage deformation, leading to formation of residual stresses. The nature of this stress distribution depends on many factors, (geometrical dimensions of the welded joint, welding mode, etc.). The zone heated in welding is covered by tensile stresses. The highest stress gradients coincide with the direction with the highest temperature gradients, i.e. residual stress distribution is typical for the field of intrinsic stresses formed under the conditions of nonuniform heating and cooling. Formation of tensile stresses caused by welding results in deterioration of the technological strength of the welded joint, which may lead to cracking in the welds and near-weld zone.

Rational development of the technology aimed at lowering the level of residual welding stresses as a result of reduction of the rigidity of welded joints and stress raisers allows avoiding cold cracking or facilitating their prevention using technological measures.

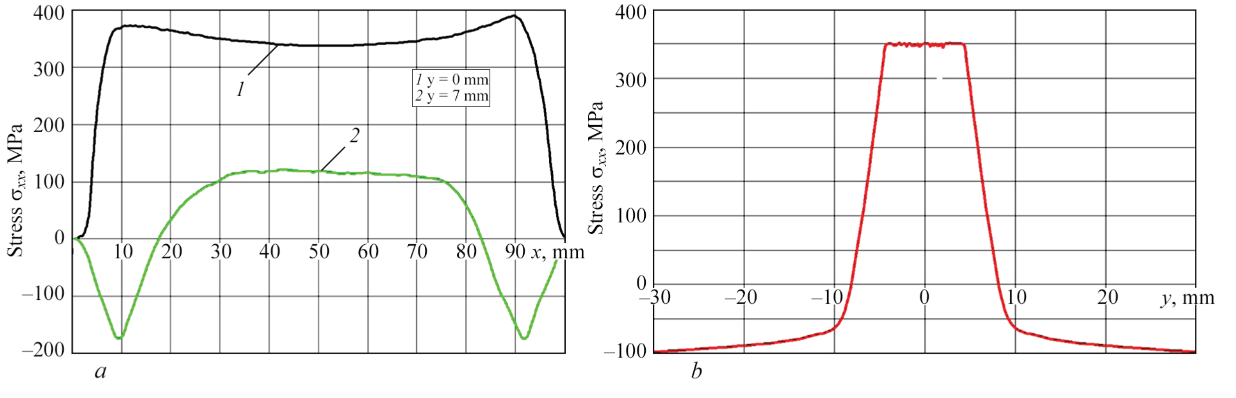

Figure 4. Distribution of residual longitudinal welding stresses: *a* — by welded plate length; *b* — in welded joint cross-section

DEVELOPMENT OF THE TECHNOLOGY OF EBW WITH A CONTROLLED COOLING RATE

Investigations by the authors of [11] conducted at PWI revealed that it is necessary to perform sample preheating to 450 °C prior to EBW, in order to prevent cold cracking in the welds at the heating stage.

Considering the above-said, we selected the temperature of 450 °C for preheating of the alloy at EBW. This method decreases the rate of temporary stress increase in welding and lowers the level of residual welding stresses [11].

Figure 5 shows a sample of 3 mm intermetallic of TiAl system, which was made by EBW with preheating in the following mode:

$$T_{\text{pre-heat}} = 450\ °\text{C},\ U_{\text{acc}} = 60\ \text{kV};\ I_{\text{b}} = 35\ \text{mA};$$
$$V_{\text{w}} = 7\ \text{mm/s};\ P = 5\cdot10^{-3}.$$

Preheating was performed by reciprocal motion of the gun with a defocused beam, which was unfolded by a special program.

As one can see from the Figure, the number of cold cracks across the welded joint on the surface of a 3 mm sample was reduced due to sample preheating up to the temperature T =450 °C before the start of the welding process, but it was not possible to completely prevent them.

As a result of theoretical studies of the stressed state by numerical experiment method it was found that preheating at the temperature of 450 °C promotes stress relaxation, and residual stresses σ_{xx} decrease by almost 40 % from 350 to 225 MPa (Figure 6).

As was noted above, stresses arising during welding, as well as the cooling rate which is ensured by local heat treatment (LHT), have a significant role in crack formation. This conclusion was the base for proposing the technological measure of welding sheet intermetallic plates with a controlled cooling rate.

This process allowed successively performing in one cycle the preheating, welding of 3 mm plates and postweld annealing, performed by a stationary gun by an unfolded electron beam for the entire sample.

Transverse stresses are also nonuniformly distributed. The middle part is exposed to tensile stresses, and the end portions — to compressive stresses. The magnitude of maximal stresses in the weld zone σ_{max} depends on weld length and, as a rule, is not higher than the value of 0.3 σ_{y} of the initial material, equal to 225 MPa in the weld center and to σ_{y} 837 MPa of the initial material. Thus, two zones can be singled out in the longitudinal direction in the butt welded joint: zone of tensile stress action and zone of compressive stress action.

The hot cracking susceptibility of the metal in welding is one of the main indices of their weldability.

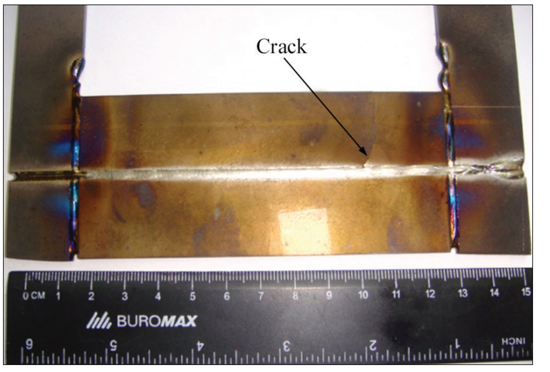

Figure 5. EB welded joint of 3 mm thick Ti–44Al–5Nb–3Cr–1.5Zr, at.% intermetallic alloy made with preheating, T = 450 °C

It ensures the technological strength of the materials in welding. Cold cracks can arise during phase and structural transformations in the solid state, practically immediately after welding.

As a result of generalization of previous research, it was shown that in addition to preheating, it is necessary to perform LHT right after welding by electron beam scanning along the weld immediately after welding is completed. It will allow lowering the rate of temporary stress increase in welding, as well as the level of residual welding stresses, which will enable lowering the cracking probability.

To solve this important task, as well as to optimize the structural and phase state of the intermetallic, the modes of welded joint LHT by the electron beam were developed.

In this case, postweld heat treatment was provided by the following program: immediately after completion of welding the electron gun was brought to the weld middle, the electron beam was unfolded and focused to the required configuration to one and to the other side from the weld middle to its end by a special computer program. It continued to heat the surface of the entire product in modes allowing compensation of excess heat removal and ensuring such a cooling rate which was taken by us as the optimal one. The frequency of electron beam scanning is 100 Hz, and the welding current decreases by 1/3.

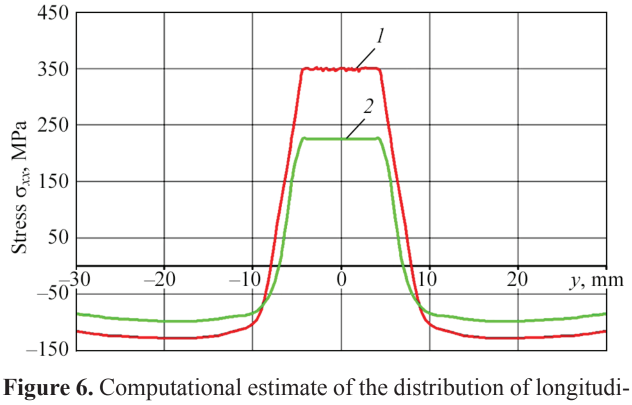

Figure 6. Computational estimate of the distribution of longitudinal residual stresses in the welded joint cross-section: *1* — without preheating; *2* — with preheating of the sample

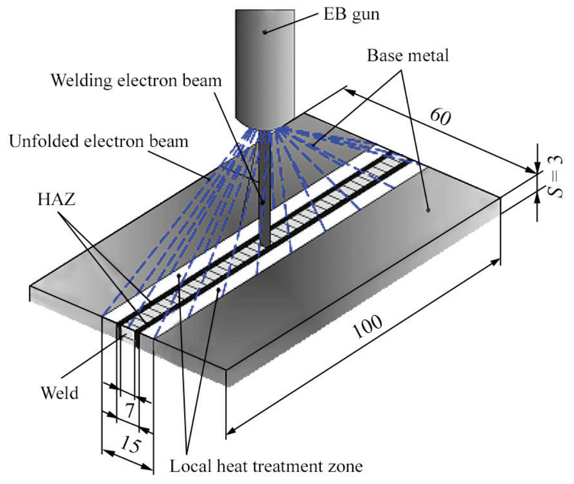

Figure 7. Scheme of EBW process with preheating and local heat treatment with a regulated cooling rate

The scheme of heat treatment with a controlled cooling rate is shown in Figure 7.

The total time of the abovementioned heat treatment was 10 min. Here, the welded joint temperature of 1000 °C was maintained for 5 min. The temperature of 1000 °C was selected because it was found earlier that appearance of β-phase as a result of phase transformations at cooling from the temperature of ~1000 °C has a plasticizing effect on the weld metal, thus increasing its ductility and toughness. After that, owing to a slow (~ 5 min) decrease of current by a special program, in keeping with the dependence, as shown in Figure 8, the welded joint was cooled to 500 °C temperature [12]. Then the electron gun was switched off, and slow cooling of the sample occurred. At slow cooling α-phase is transformed into lamellar ($\gamma+\alpha_2$)-phase, and a certain amount of B2-phase is preserved in the alloy, which is an ordered structure of β_0-phase [13].

EBW and LHT performed by the above scheme result in reduction of the rate of temporary stress increase and of the level of residual welding stresses. It allows avoiding the appearance of cold cracks and producing defectfree joints. These technological recommendations were used to produce a defectfree welded joint of 3 mm thick plates (Figure 8). Figure 9

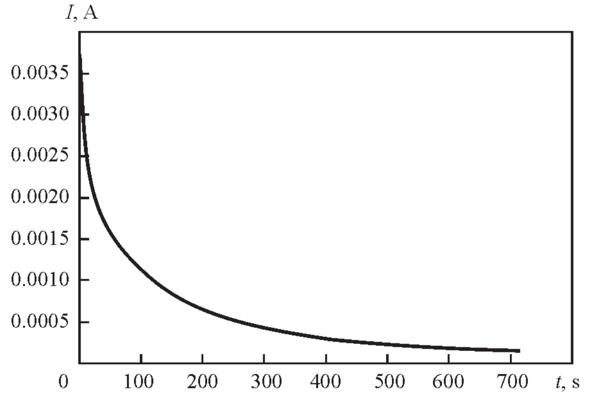

Figure 8. Dependence of current change on time to ensure controlled cooling of the weld across its thickness δ = 3 mm [10]

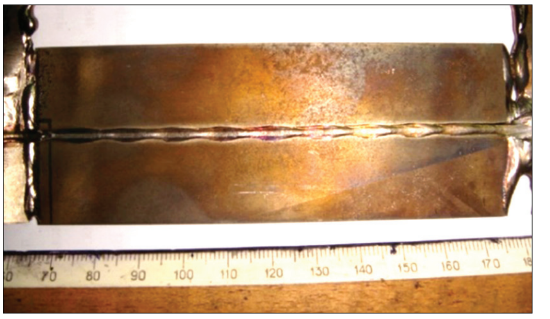

Figure 9. A sample of intermetallic alloy Ti–44Al–5Nb–3Cr–1.5Zr, at.%, δ = 3 mm after EBW and heat treatment by the scheme shown in Figure 7

shows the appearance of 3 mm thick sample, welded by the proposed scheme. The thermal cycle of the process of EWB of 3 mm intermetallic with preheating and local controlled annealing is shown in Figure 10.

Figure 10 also shows phase transformations during EBW with preheating and subsequent local heat treatment of 3 mm thick samples, which represent the structural transformations and fracture surface at different process stages.

As one can see from Figure 10, the weld metal has a three-component structure: γ-phase matrix, ($\gamma+\alpha_2$)-phase colonies and precipitates of residual δ-phase on the colony boundaries. Such a structure leads to increase of the HAZ ductility in 3 mm thick samples.

Moreover, the microhardness of all the regions of this sample subjected to preheating and subsequent local heat treatment is lower than the hardness of samples made without LHT application, as heat accumulation occurs, which leads to lowering of the sample cooling rate, and of internal stresses, respectively.

In work [10] it was established that at cooling of the intermetallic weld from 1000 °C temperature phase transformation takes place, due to which an additional β_0 (B2) phase appears in the structure, which is a Ti-based ordered phase. It is located on the colony boundaries and blocks crack initiation and propagation in α_2-phase as a result of stress lowering. Formation of a favorable three-component structure in the weld: γ-phase, ($\gamma+\alpha_2$)-phase and β-phase promotes an increase of its strength and ductility.

Fractures of welded joints of 3 mm thick titanium aluminides, welded with a controlled cooling rate, demonstrate a mixed fracture mode (with 30 % of the ductile component).

Fractogram of welded joint fracture surface reveals that cleavage facets observed in the fracture, are separated by tear regions, which are due to plastic shear.

Figure 11 shows that the stressed state of 3 mm thick intermetallic welded joint after LHT which allows lowering the level of residual welding stresses, ensures a slow cooling rate of the welded joints.

The cooling rate in this case decreased from 0.7 to 0.9 °C/s. In this connection, the residual welding

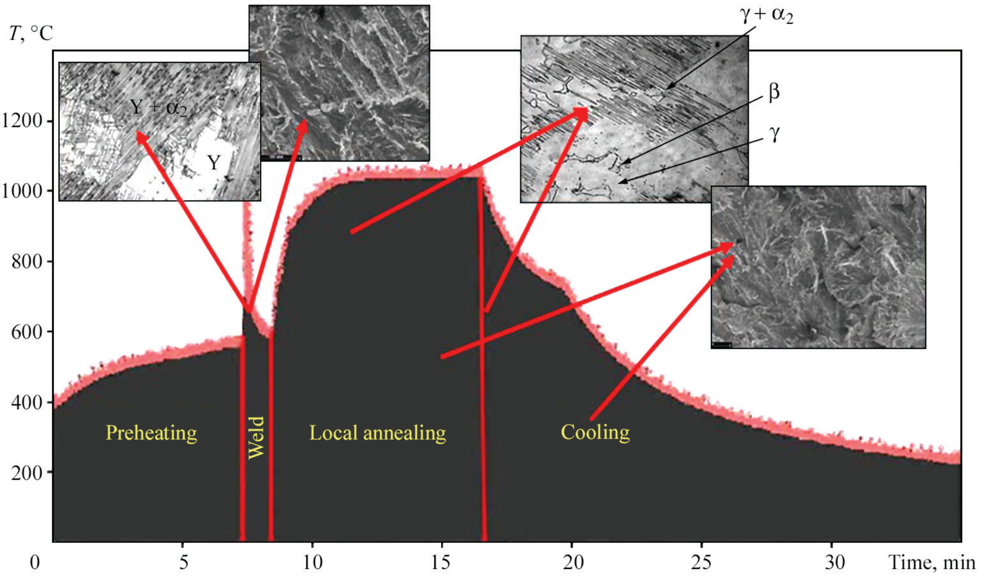

Figure 10. Influence of local heat treatment on the structural state of the welded joint of intermetallic alloy Ti–44Al–5Nb–3Cr–1.5Zr, at.%

Table 2. Ultimate strength of EB welded joints with LHT

Sample number	Thickness δ, mm	Value σ_t, MPa	Fracture site
1	3	310.9	BM
2	3	319.1	BM

Table 3. Ultimate strength of the intermetallic welded joints produced by EBW without LHT

Sample number	Thickness δ, mm	Value σ_t, MPa	Fracture site
1	3	197.8	BM
2	3	152.1	BM
3	3	175.5	BM

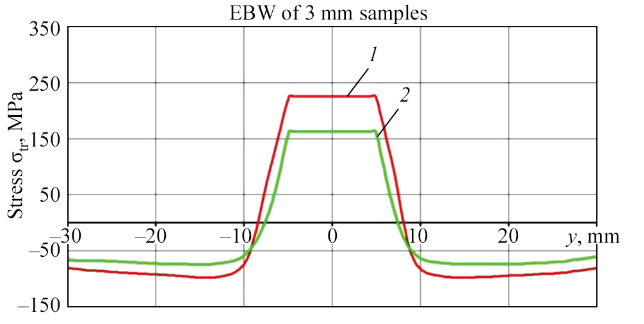

Figure 11. Computational evaluation of the distribution of residual longitudinal stresses in the cross-section of intermetallic welded joint, δ = 3 mm after: *1* — EBW with preheating; *2* — EBW with preheating and annealing at T = 1000 °C, t = 5 min

stresses decreased by almost 30 % and were equal to 162 MPa (Figure 11).

The data for plotting the graphs were derived using a mathematical model. The graph shows the changes in temperature, stressed state and cooling rate at application of this kind of heat treatment of 3 mm thick samples at the cooling stage. As one can see from the Figure, after 500 °C the change of sample temperature occurs very slowly. Here, the stresses are equal to 180 MPa.

The shape of σ_x curve is associated with a small width of the plate, at which the compressive stresses in its cross-section do not reach zero values.

Prevention of cold cracking and producing a defectfree joint due to a controlled cooling rate occur through lowering of the residual welding stresses, as well as formation of an optimal structure [14].

A lower level of stresses in the weld is attributable to formation of β-phase during cooling after welding, which promotes a significant relaxation of temporary stresses [10].

Static tensile testing was performed to assess the welded joint strength [14]. Results of mechanical testing of welded joint samples, obtained during tensile testing are given in Table 2.

Mechanical testing of welded joints of samples made by EBW without LHT was conducted for comparison. Table 3 gives the test results.

As one can see from Tables 2 and 3, the ultimate strength values in samples welded using postweld local heat treatment are much higher than for samples produced without LHT application.

Analysis of the test data showed that postweld local heat treatment has a positive influence on the level of strength at mechanical testing, namely it allows increasing the ultimate strength of the welded joint approximately 1.8 times by average values from 175 to 315 MPa [15].

Thus, preheating and further postweld heating of the products, as well as selection of the optimal welding modes have a positive influence on reduction of the possibility of cracking.

CONCLUSIONS

1. It was established that in order to prevent cold cracking in welding sheet plates of TiAl system intermetallic, it is necessary to conduct preheating of the samples

and postweld local heat treatment of the welded joints. It was numerically demonstrated and experimentally confirmed that use of the distributed source of sample preheating before welding allows providing favourable conditions during welding and at further cooling, namely lowering the tensile stress magnitude.

2. A technology of electron beam welding of intermetallic has been developed, which envisages successive performance in one chamber of preheating, and electron beam welding of the intermetallic with postweld local heat treatment.

3. Modes of controlled cooling of 3 mm thick plates were proposed, which allow compensation of excess surface heat removal.

4. At application of this technology for 3 mm thick samples, it is recommended to perform heat treatment by an electron beam unfolded and defocused to one and the other side from the weld middle to its end with gradual lowering of its power using a special computer program. Here, the optimal welded joint cooling rate, which lowers the level of residual welding stresses by almost 30 % from 225 to 160 MPa and allows avoiding cracking in the weld is the rate of 0.7–0.9 °C/s.

5. Mechanical tensile testing of welded joints showed that sample fracture occurs through the initial material. Application of local heat treatment increases the level of ultimate strength of the welded joint approximately 1.8 times.

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ORCID

E.L. Vrzhyzhevskyi: 0000-0001-8651-8510,
N.V. Piskun: 0000-0003-1459-2310,
O.A. Velykoivanenko: 0009-0007-3704-2000,
I.I. Statkevych: 0000-0001-9403-2123,
T.G. Taranova: 0000-0002-2656-4693

CONFLICT OF INTEREST

The Authors declare no conflict of interest

CORRESPONDING AUTHOR

N.V. Piskun
E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine.
E-mail: nadamova54@gmail.com

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