https://doi.org/10.37434/tpwj2022.01.06

INFLUENCE OF TIME OF EXISTENCE OF MOLTEN POOL IN ELECTRON BEAM PROCESSES ON THE LEVEL OF EVAPORATION OF ELEMENTS WITH A HIGH VAPOR TENSION

N.V. Piskun, E.L. Vrzhyzhevskyi, V.A. Kostin, T.G. Taranova, I.L. Bogaichuk, I.I. Statkevych

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

ABSTRACT

The intermetallic Ti–44Al–5Nb–3Cr–1.5Zr alloy (at.%), developed and melted at the E.O. Paton Electric Welding Institute of the NAS of Ukraine, was studied. The processes of evaporation of elements with a high vapor tension, such as aluminium and chromium for two electron beam processes: melting and welding were studied. It was experimentally proven and confirmed by investigations that the use of directional crystallization by electron beam melting, which takes place in deep vacuum conditions, does not allow providing uniformity of structure along the length of the ingot, which is associated with evaporation of elements with a high vapor tension, such as aluminium and chromium. It was found that during electron beam welding of specimens of intermetallic Ti–44Al–5Nb–3Cr–1.5Zr alloy (at.%), cracks appeared, but, as was proved by X-ray spectral studies, evaporation of elements does not occur. The parameters of these two processes were compared and it was shown that the level of evaporation of elements with a high vapor tension in electron beam processes is influenced by the time of staying the material in a liquid state and the sizes of the molten zone.

KEY WORDS: intermetallic alloy of TiAl system, electron beam melting, electron beam welding, evaporation, elements with a high vapor tension, molten zone, crystallization time

INTRODUCTION

It is known that heat-resistant intermetallic alloys have high strength, heat resistance, creep and corrosion resistance at high temperatures [1]. Thanks to a low density and specific strength, intermetallics based on γ-TiAl are attractive for the use in gas turbine engines [2]. Due to unique properties, they are also promising for using in various other industries. For example, manufacture of low-pressure turbine blades from these alloys allows saving 180 kg for each engine as compared to traditional materials [3]. This, in turn, allows reducing the cost of products of aerospace industry, which is very important.

However, a low ductility at room temperature and a low manufacturablity, associated with the latter, complicates and in some cases even excludes the possibility of manufacturing semi-finished products and products from these materials. A widespread use of titanium aluminides in the structures of different purpose depends to a large extent on the creation of effective methods for their manufacturing and subsequent processes of their mechanical and heat-mechanical treatment.

Since the use of TiAl titanium aluminides is promising for its wide application in the structures of aircraft engine turbines, parts of the automotive industry and some other industries [4], then the introduction of intermetallic alloys largely depends on the development of technologies of their joining. In parts and assemblies of gas turbine engines, it is possible to use welding in order to simplify their manufacturing. The most suitable method for producing intermetallic joining is electron beam welding [5], which allows welding products of different geometric shapes and producing welds of different extension. In addition, as compared to other types of fusion welding, it has the following advantages: first, since it is carried out in a high vacuum, it fully protects such an active material as titanium; secondly, in electron beam welding, a narrow weld and a very small heat-affected zone are formed, which, in turn, should lead to minimal deformations of welded joint.

Therefore, the development and optimization of welding technology, the creation of new approaches to the welding process in order to produce defectless joints is very relevant.

The main problem with the use of electron beam processes for the manufacture and treatment of titanium alloys is vacuum evaporation of elements with a high vapor tension [6, 7]. These elements include, in the first turn, aluminium and chromium. Since aluminium is one of the main elements of the alloy, its evaporation affects the structure and, accordingly, mechanical properties of the alloy.

The aim of the work is to study the influence of electron beam zone melting modes and electron beam welding of intermetallic Ti–44Al–5Nb–3Cr–1.5Zr al-

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

loy (at.%) on the processes of evaporation of alloying elements and formation of microstructure and properties.

MATERIAL AND PROCEDURE OF RESEARCH

In the work, the intermetallic alloy of the following composition was investigated: Ti–44Al–5Nb–3Cr–1.5Zr (at.%) (Table 1), which was developed and melted at the E.O. Paton Electric Welding Institute of the NAS of Ukraine (PWI) [8].

Specimens for the study were produced after electron beam crucibleless zone melting (Figure 1) and after electron beam welding (Figure 2).

At a room temperature, cast intermetallic alloys of the TiAl system represent low ductililty materials and during their testing to a uniaxial tension, a fracture of the specimen occurs immediately in an elastic area after tension.

It is known that before using cast intermetallic to eliminate these defects, it should be subjected to gas static isothermal compression (GSIC), long-term heat treatment or rolling [9]. One of the methods to improve the structure and increase mechanical characteristics of intermetallic is a directed crystallization.

For conducting research, the method of crucibleless electron beam zone melting was used (Figure 1).

In our opinion, the use of a crucibleless electron beam melting method is quite promising for the mentioned purposes, because it has a number of distinguishing features:

● high thermal efficiency (efficiency of the process reaches 90 %), which is associated with a small power consumption;

● the indicated method makes it easy to regulate and maintain a set length of the molten zone, which is essential in developing both scientific bases and practical realization of the process;

● treatment of materials can be carried out in a wide range of temperatures — 250–2200 °C, which allows remelting an intermetallic alloy having a melting point of 1460 °C;

● this method allows an easy control of a beam with its direct influence on a specimen. Scanning the beam along the molten zone with a certain frequency and amplitude can, respectively, change the temperature gradient of specimens in the process of melting.

It is also noticeable that after a directed recrystallization, GSIC treatment is not required, because in the

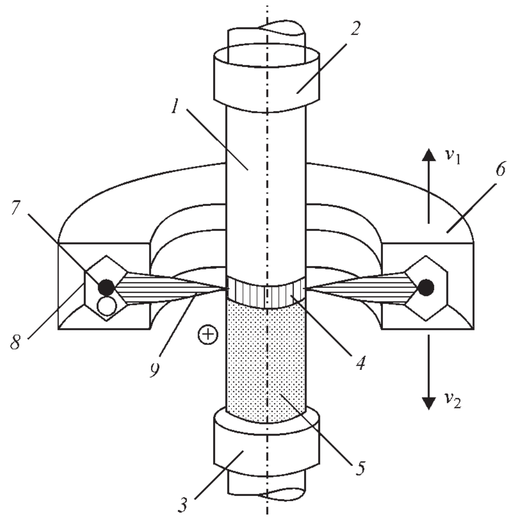

Figure 1. Scheme of the method of crucibleless electron beam zone melting: *1* — molten specimen; *2* — upper holder; *3* — lower holder; *4* — molten zone; *5* — remelted area; *6* — electron beam heater; *7* — cathode; *8* — focusing device; *9* — electron beam

produced ingots such microdefects as discontinuities, microcracks, etc. are absent; the porosity is absent, because shrinkage goes directed at the front of crystallization and not in the volume of the ingot. It allows providing its uniform structure along the length of the ingot. In addition, the conditions of the process provide the purity of the material that is melted (there is no interaction with the material of the crucible).

As was mentioned above, for the further use of this alloy in industry, the technology of electron beam welding (EBW) of intermetallic of the following nominal composition of Ti–44Al–5Nb–3Cr–1.5Zr (at.%) was developed. That was the same alloy, which was tried to be treated by the method of electron beam melting.

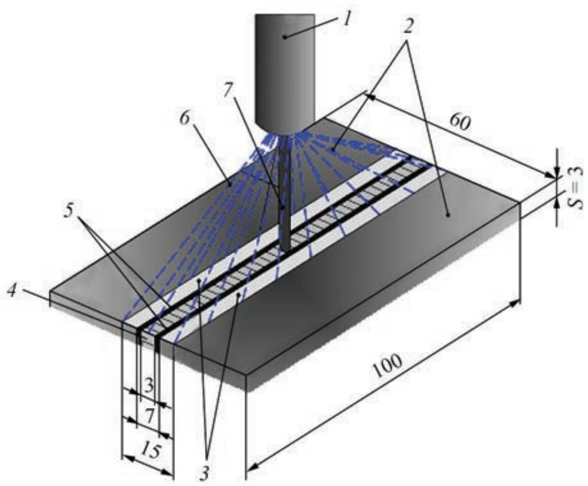

Figure 2. Scheme of the process of electron beam welding of plates of intermetallic Ti–44Al–5Nb–3Cr–1.5Zr alloy (at.%) in the welding chamber of the UL-144 installation: *1* — electron beam gun; *2* — base material; *3* — zone of local heat treatment; *4* — weld; *5* — heat-affected zone; *6* — deployed beam of electrons; *7* — electron welding beam

The experiments on electron beam welding of intermetallic were performed in the welding chamber of the UL-144 installation according to the scheme shown in Figure 2.

Electron beam welding was performed without heating in the following mode: U_{acc} = 60 kV; I_b = = 35 mA; v_w = 7 mm/s; $P = 5 \cdot 10^{-3}$ Pa.

While producing welded joints of intermetallics of the TiAl system by the EBW method, their significant disadvantage is the possibility of cold crack formation, that occur at temperatures below 700 °C.

RESEARCH RESULTS

ELECTRON BEAM CRUCIBLELESS ZONE MELTING

During the technological experiments on electron beam crucibleless melting of intermetallic of the TiAl system, a strong evaporation from the molten zone and areas of the heated solid surface, occured. Unfortunately, the evaporated elements were deposited on assemblies of the electron beam heater, including such an important assembly as a tantalum spiral that simulates electrons; illuminator glass panes; chamber walls; fittings, which led to the impossibility of completing the process.

Micro-X-ray spectral examinations showed that in the process of electron beam melting of the intermetallic of the system Ti–44Al–5Nb–3Cr–1.5Zr (at.%), a strong evaporation of aluminium — one of the main components of the alloy occurs, which has a high vapor tension. This occurs from the molten zone and areas of a solid surface that are heated. In addition, chromium, included in titanium aluminide as an alloying element, also evaporates quite intensively. The studies of the chemical composition of titanium aluminide, subjected to recrystallization during crucibleless electron beam melting, showed that from the material up to 20 % of aluminium and up to 18 % of chromium evaporate.

Examinations of the structure of titanium aluminide ingots produced by electron beam crucibleless melting (Figure 3) showed that the structure contains areas of two types: light- and dark-etched coarse equilibrium grains (Figure 3, *a*).

The examination of the microstructure of the ingot showed the presence of areas of the specimen in which the colonies of lamellae of the γ-phase are located in different directions (Figure 3, *b*). Figure 3, *c* presents the macrostructure of the cross-section of the specimen. Tiny pores are observed, from which microcracks propagate to the central part of the specimen, which is apparently caused by intense evaporation of aluminium. On the opposite edge of the cross-section of the specimen (Figure 3, *d*), the areas

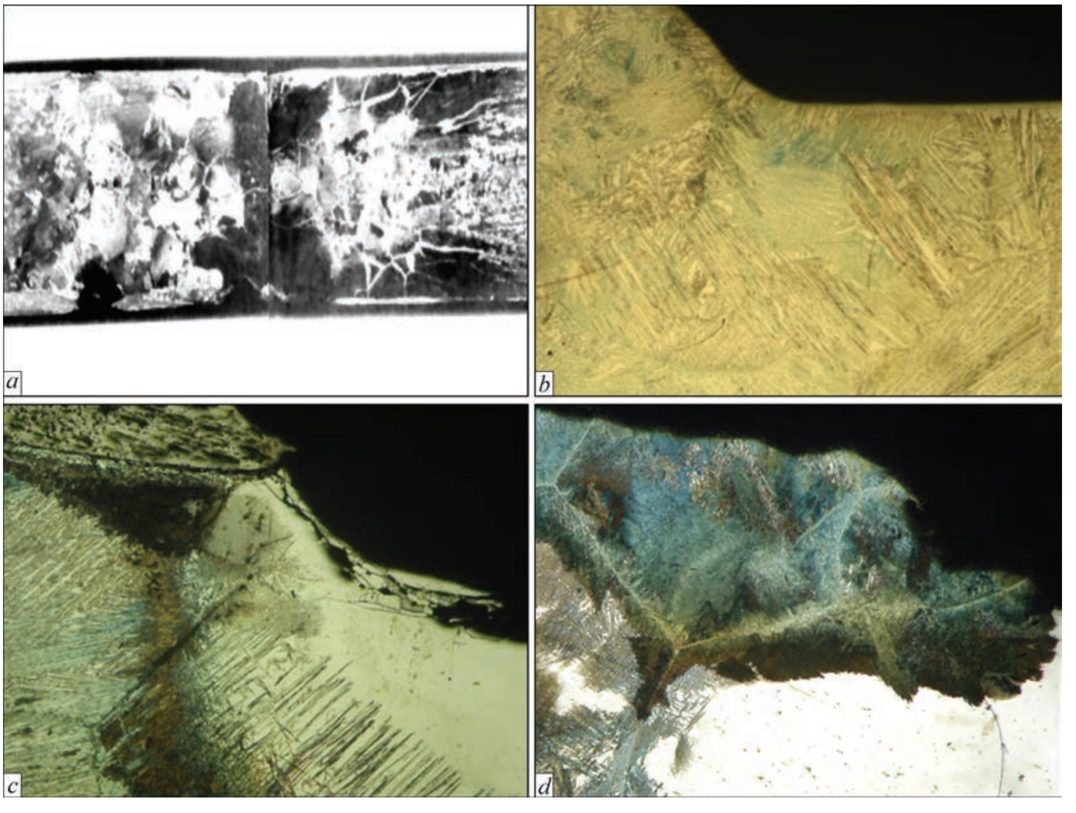

Figure 3. Structure of titanium aluminide ingots produced by electron beam crucibleless zone melting: *a* — macrostructure of investigated specimens; *b* — specimen area, on which the colonies of lamellae of the γ-phase are seen, located in different directions; *b*, *c*, *d* — macro- and microstructure of the cross-section of the specimen after zone remelting

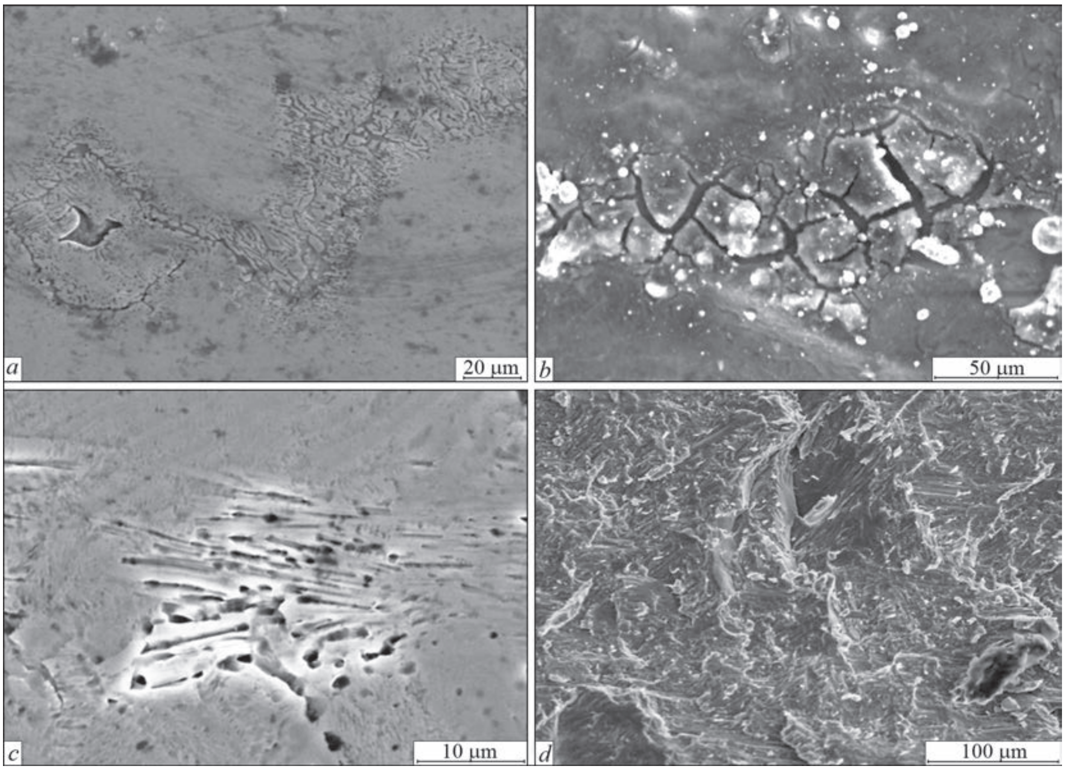

Figure 4. Fractographic studies of specimens of intermetallic Ti–44Al–5Nb–3Cr–1.5Zr alloy (wt.%) after electron beam zone melting: *a–c* — regions of the pore bottom of intermetallic; d – fracture surface of the pore bottom of intermetallic

of coarse grains are located, consisting of a mixture of $\gamma+\alpha_2$-phase.

The micro-X-ray spectral analysis of the bottom of the pore, performed in the electron scanning microscope JSM-840, showed that the assumptions made above were correct (Figure 4). Fractographic studies of specimens of intermetallic Ti–44Al–5Nb–3Cr–1.5Zr alloy (at.%) after electron beam zone melting showed the presence of a large number of pores (Figure 4, *c*).

Examinations showed that at the boundaries of the pore, the aluminium content drops to 18–20 at.% as compared to 46–47 wt.% in the matrix. At the bottom of the pores, the areas of the film with a high aluminium content were found. At some points, the aluminium content reached 59 wt.%. It is possible, that the formation of aluminium oxides occurred in these places (Figure 4, *b*). During a detailed study of fractures, the areas in the form of microscopic particles were found. As was shown by X-ray spectral analysis, the chromium content in these precipitations reached 18 %. For comparison — in the alloy, the chromium content is 3 %.

ELECTRON BEAM WELDING OF INTERMETALLIC ALLOY

Examination of welded butt joints after electron beam welding (EBW) showed that in the weld, transverse cold cracks (Figure 5, *a*) are observed, which pass through the welded joint and end on both sides of the specimen on the base material. It is necessary to note the heterogeneity of the structure of the weld metal in the form of colonies of the $(\gamma+\alpha_2)$-phase, which are located along the fusion zone and have a microhardness of 5110–5270 MPa. In this area, numerous cracks with a length from 100 to 300 μm were revealed, located parallel to the fusion line (Figure 5, *b*).

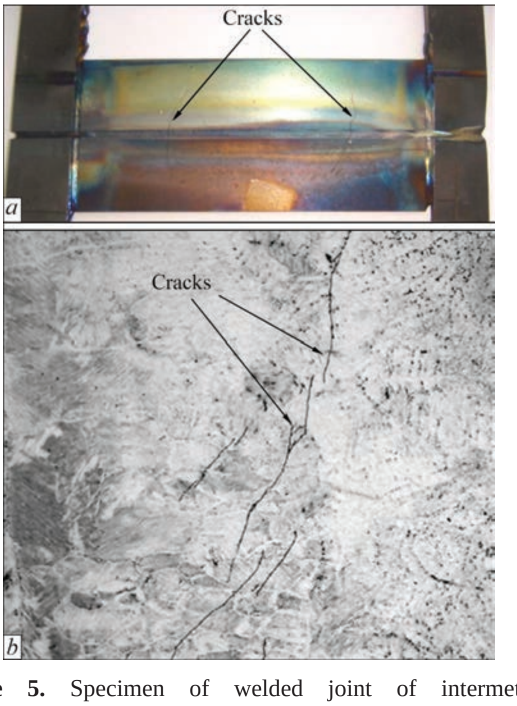

Figure 5. Specimen of welded joint of intermetallic Ti–44Al–5Nb–3Cr–1.5Zr alloy (at.%), produced by electron beam welding: *a* — general appearance; *b* — microstructure (×200) of weld metal

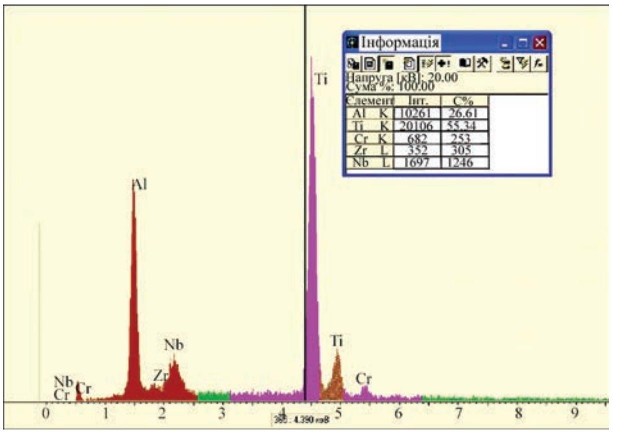

Figure 6. Quantitative analysis of welded joint zone of intermetallic of the Ti–44Al–5Nb–3Cr–1.5Zr system (wt.%)

As it was found above, if in electron beam melting a considerable evaporation of aluminium (to 20 %) and chromium (to 18 %) occurs, and in electron beam welding cracks appear, it became necessary to determine the reasons of cold crack formation. This may be associated with the problem of evaporation of elements during electron beam welding, which leads to changes in the composition of aluminium or chromium.

In order to determine the possible evaporation of the alloy elements in the process of electron beam welding, a quantitative X-ray spectral analysis of the intermetallic welded joint produced by the EBW method was performed.

The results of the quantitative analysis of the welded joint elements of the intermetallic Ti–44Al–5Nb–3Cr–1.5Zr (at.%) are presented in Figure 6.

Investigation of evaporation of elements in the process of welding is almost not observed. Difference in the elemental composition occurs in aluminium by 2.2 % and in chromium by 1 %. In this case, the redistribution of element components in the weld and titanium occurs approximately by 2.5 % higher than in the initial condition. Chromium and aluminium are the elements with a high vapour tension, and aluminium, in addition, has a low boiling point and manages partially to evaporate in the welding process.

On the surface of the welded joint of the intermetallic of the Ti–44Al–5Nb–3Cr–1.5Zr system (at.%), performed by EBW, parallel formations are observed both in the base metal as well as in the weld metal (Figure 7, *a*).

The thickness of these phases amounts to 1.36–2.5 μm. Cracking in these phases is not observed. Quantitative analysis of the phases showed that they are enriched in titanium (Figure 7, *b*).

DISCUSSION

COMPARISON OF MODES OF THE ELECTRON BEAM MELTING PROCESS AND ELECTRON BEAM WELDING OF THE Ti–44Al–5Nb–3Cr–1.5Zr ALLOY

Thus, according to the data of chemical analysis and structural examinations, as well as on the basis of a detailed study of literary sources devoted to the topic of evaporation of elements with a high vapour tension in electron beam processes [6, 7], it was concluded that using the method of crucibleless electron beam melting, it is not possible to produce high-quality ingots. In connection with the abovementioned, it was decided to apply an induction heating in argon, that allowed solving all problems with evaporation of elements and producing high-quality ingots [10, 11].

As showed the results of previous studies, the main source of cracks arising is a low ductility of intermetallic at room temperatures (the temperature of viscous-brittle transition is 700 °C) and inability to resist the appearance of cracks as a result of formation of welding stresses.

In order to prevent cold crack formation in welded joints of specimens of titanium aluminide and to form a high-quality weld, it was necessary to carry out a preheating heating of the specimens [12, 13] and the next local heat treatment by an electron beam, deployed in the one and the other direction. It was

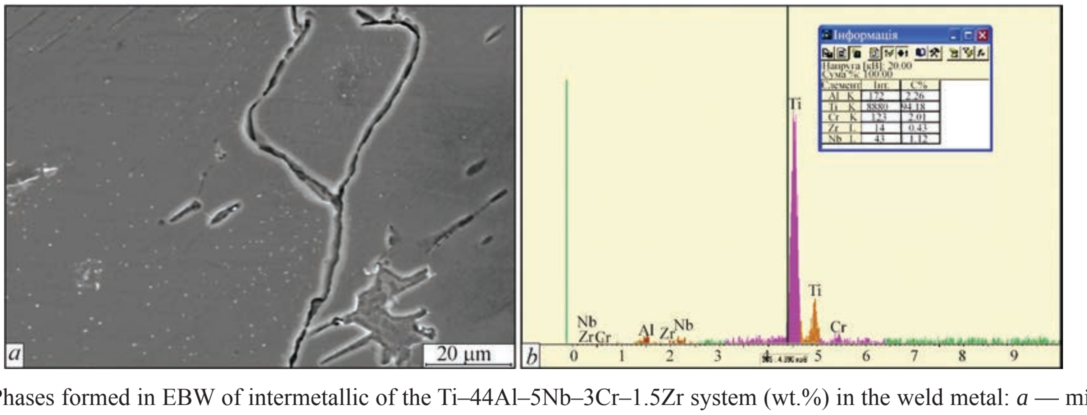

Figure 7. Phases formed in EBW of intermetallic of the Ti–44Al–5Nb–3Cr–1.5Zr system (wt.%) in the weld metal: *a* — microstructure; *b* — spectral analysis of phases

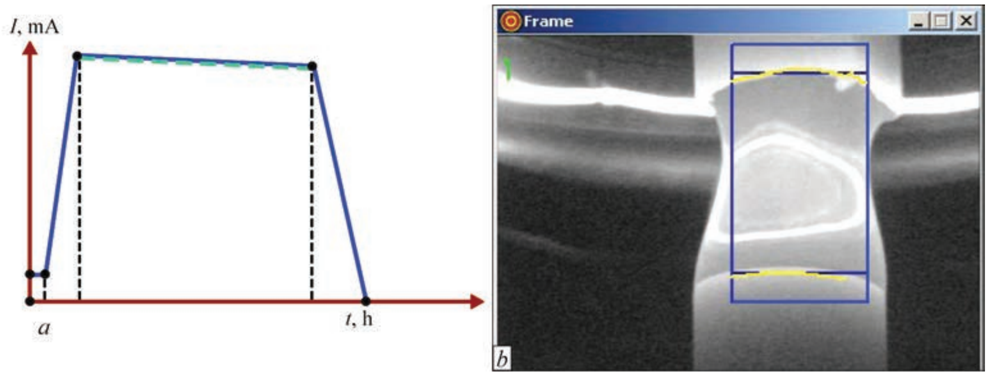

Figure 8. Characteristics of electron beam melting process: *a* — thermal cycle of the process of zone melting of intermetallic; *b* — size of molten zone in the process of zone melting is 10 mm

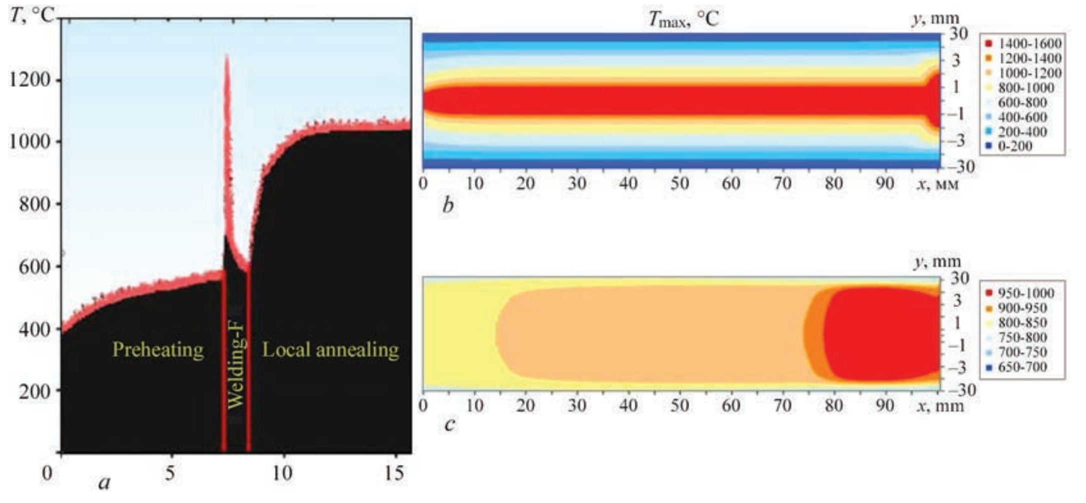

Figure 9. Characteristics of the process of electron beam welding: *a* — thermal cycle of EBW process for welding intermetallic; *b* — calculation of temperature distribution in the weld of intermetallic with the thickness of 3 mm in the process of EBW; *c* — calculation of temperature distribution in the weld of intermetallic within 1 s after the end of welding process

numerically shown and experimentally confirmed that the use of a distributed source of a preheating of the specimen before welding allows realizing favorable conditions during welding and during further cooling, namely, reducing the value of tensile stresses by 30 %. In addition, during use of this technology, a phase transformation occurs, due to which an additional β-(B2)-phase appears in the structure, which represents an ordered phase based on Ti. It is located on the boundaries of colonies and blocks the initiation and propagation of cracks in the α_2-phase as a result of stress reduction. The formation of a favorable three-component structure: γ-phase, $(\gamma + \alpha_2)$-phase and β-phase in the weld contributes to increase in its strength and ductility [14, 15].

To answer the question, why during two electron beam vacuum processes for the same alloy, absolutely different behavior of elements with a high vapour tension was observed, a comparison of basic characteristics of these processes was conducted. Figures 8, 9 show the characteristics of the process of electron beam melting and electron beam welding.

As is seen from Figure 7, in electron beam melting at a speed of 50 mm/h, the duration of staying the material in a liquid state is 720 s. At a small thickness of welded material, it can be accepted that geometric dimensions of the welding pool in arc and electron beam welding are approximately equal [16].

To evaluate the average duration of staying the metal in a liquid state during electron beam welding, the formulas were used given in [17], and the dimensions of the welding pool, which are usually accepted for arc welding of titanium with a thickness of 3 mm. By the calculations, it was found that the welding pool in electron beam welding stays in a liquid state approximately for 0.7 s, which is more than 700 times lower than in electron beam melting.

In addition, the width of the molten zone, which is crystallized in electron beam melting, is 10 mm (Figure 7, *b*), which is much more than in the process of electron beam welding, in which the width of the weld with the heat-affected zone is not more than 3 mm. And already in a second after the end of the welding process (Figure 9, *c*), the temperature in the weld drops by 500 °C.

CONCLUSIONS

It was found that in the process of electron beam melting of the intermetallic Ti–44Al–5Nb–3Cr–1.5Zr alloy, a strong evaporation of elements occurs, that have a high vapour tension: aluminium to 20 % and chromium to 18 %. Since aluminium is one of the main components of alloy elements, its evaporation affects the structure. In electron beam welding, such a phenomenon is not observed.

As compared to thermocycles of two electron beam processes, it turned out that duration of staying the material in a liquid state during electron beam melting is 720 s, width of the molten zone is 10 mm, and in electron beam welding, a welding pool, which is crystallized in 0.7 s, has dimensions of approximately 2 mm.

Thus, the level of evaporation of elements with a high vapour tension in electron beam processes depends on duration of staying the material in the liquid state and sizes of the molten zone.

REFERENCES

1. Schwaighofer, E., Clemens, H., Mayer, S., et al. (2014) Microstructural design and mechanical properties of a cast and heat treated intermetallic multiphase γ-TiAl based alloy. *Intermetallics*, **44**, 128–140. DOI: https://doi.org/10.1016/j.intermet.2013.09.010
2. Bewlay, B.P., Nag, S., Suzuki, A., Weimer, M.J. (2016) TiAl alloys in commercial aircraft engines. *Mater. High Temp.*, **33**, 549–559. DOI: https://doi.org/10.1080/09603409.2016.1183068
3. Clemens, H., Mayer, S. (2016) Intermetallic titanium aluminides in aerospace applications processing, microstructure and properties. *Mater. High Temp.*, **33**, 560–570. DOI: https://doi.org/10.1080/09603409.2016.1163792
4. Kablov, E.N., Lukin, V.I. (2008) Intermetallic based on titanium and nickel for advanced engineering product. *The Paton Welding J.*, **11**, 65–71.
5. Chernobaj, S.V. (2013) Welding of titanium aluminide alloys (Review). *Ibid.*, **8**, 25–30.
6. Varich, I.Yu., Akhonin, S.V., Trigub, N.P. et al. (1997) Evaporation of aluminium from titanium-based alloys during cold-hearth electron beam melting. Problemy *Spets. Elektrometallurgii*, **4**, 15–21[in Russian].
7. Paton, B.E., Trigub, N.P., Akhonin, S.V. et al. (2006) *Electron beam melting of titanium*. Kiev, Naukova Dumka [in Russian].
8. Zhuk, G.V., Trigub, N.P., Zamkov, V.N. (2003) Producing of titanium gamma-aluminide ingots using EBTHM method. *Advances in Electrometallurgy*, **4**, 19–21.
9. Imaev, V.M., Imaev, R.M., Khismatullin, T.G. (2008) Mechanical properties of intermetallic alloy Ti–43Al–7(Nb, Mo)–0.2B (at.%) after heat treatment. *Fizika Metallov i Metallovedenie,* 105(**5**), 516–522 [in Russian]. DOI: https://doi.org/10.1134/S0031918X08050098
10. Kartavykh, A.V., Asnis, E.A., Piskun, N.V. et al. (2015) Microstructure and mechanical properties control of γ-TiAl(Nb, Cr, Zr) intermetallic alloy by induction float zone processing. *J. of Alloy and Compounds*, **643**, 182–166. DOI: https://doi.org/10.1016/j.jallcom.2014.12.210
11. Kartavykh, A.V., Asnis, E.A., Piskun, N.V. et al. (2017) Room-temperature tensile properties of float-zone processed β-stabilized γ-TiAl(Nb, Cr, Zr) intermetallic. *J. Materials Letters*, **188**, 88–91. DOI: https://doi.org/10.1016/j.matlet.2016.10.103
12. Kim, Y.-W., Smarsly, W., Lin, J. et al. (2014) Electron beam joining of γ-titanium aluminide. Gamma Titanium Aluminide Alloys 2014. *The Minerals, Metals & Materials Society*, 99–103.
13. Vrzhyzhevskyi, E.L., Piskun, N.V., Taranova, T.G. et al. (2019) Prevention of cold cracks formation during electron-beam welding of alloy based on TiAl system intermetallic compound. *Tekhnologicheskie Sistemy*, 86(**1**), 43–49 [in Russian]. DOI: https://doi.org/10.29010/86.6
14. Tang, B., Qi, X.S., Kou, H.C. et al. (2016) Recrystallization behavior at diffusion bonding interface of high Nb containing TiAl alloy. *Advanced Engineering Materials*, 18(**4**), 657–664. DOI: https://doi.org/10.1002/adem.201500457
15. Yang, K.L., Huang, J.C., Wang, Y.N. (2013) Phase transformation in the β-phase of super a2 Ti_3Al base alloys during static annealing and super plastic deformation at 700–1000 °C. *Acta Mater.*, **51**, 2577–2594. DOI: https://doi.org/10.1016/S1359-6454(03)00057-0
16. Paton, B.E. (1987) *Electron beam welding*. Kyiv, Naukova Dumka [in Russian].
17. Petrov, G.L., Tumarev, A.S. (1977) *Theory of welding processes*: Manual for higher educ. inst., 2nd Ed. Moscow, Vysshaya Shkola [in Russian].

ORCID

N.V. Piskun: 0000-0003-1459-2310
E.L. Vrzhyzhevskyi: 0000-0001-8651-8510,
V.A. Kostin: 0000-0002-2677-4667
T.G. Taranova: 0000-0002-2656-4693,
I.I. Statkevych: 0000-0001-9403-2123

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: E-mail: nadamova54@gmail.com

SUGGESTED CITATION

N.V. Piskun, E.L. Vrzhyzhevskyi, V.A. Kostin, T.G. Taranova, I.L. Bogaichuk, I.I. Statkevych (2022) Influence of time of existence of molten pool in electron beam processes on the level of evaporation of elements with a high vapor tension. *The Paton Welding J.*, **1**, 26–32.

JOURNAL HOME PAGE

https://pwj.com.ua/en

Received: 25.10.2021
Accepted: 07.02.2022