WELDING OF TITANIUM ALUMINIDE ALLOYS (Review)

S.V. CHERNOBAJ
E.O. Paton Electric Welding Institute, NASU
11 Bozhenko Str., 03680, Kiev, Ukraine. E-mail: office@paton.kiev.ua

One of the most promising directions in the field of development of new metallic materials with a high level of heat resistance and thermal stability is development of intermetallic alloys of Ti–Al system. In the near future these alloys can create serious competition to nickel-based superalloys, as titanium aluminides are lighter and do not require expensive and deficit elements for alloying. In addition, they have a high corrosion resistance, high-temperature oxidation resistance, and also have a high modulus of elasticity and strength. Titanium aluminides can be successfully applied in the form of cast products, for instance of valves of super-power internal combustion engines; as high-temperature resistant coatings on gas turbine blades, exposed to high-temperature gas flows; as structural material operating at static loads and high temperatures. Wide industrial application of titanium aluminides is hindered by their low ductility at room temperature. This greatly complicates technological processing and slows down industrial application of the above alloys. Therefore, application of titanium aluminides in various-purpose structures is dependent on development of effective technologies of their processing, including welding. In this connection the purpose of this review is analysis of currently available developments of joining processes for titanium aluminide based materials by various kinds of welding. Analysis of published data given in the review showed that formation of welded joints with application of traditional welding processes based on local melting of material has several drawbacks, which can be eliminated at application of various solid-phase welding processes. Results given in the publications, are indicative of the good prospects for application of intermediate inserts for joining difficult-to-weld titanium aluminide based alloys. 36 Ref., 5 Figures.

Keywords: *titanium aluminide, fusion welding, temperature, joining processes, pressure welding, structure, insert, weld, microstructure*

Aircraft engine manufacture is an extremely complicated process based on the latest advances in the field of aero- and thermodynamics, materials science, technology, strength, electronics and informatics. Important tasks solved when designing new generation engines are lowering of the cost of manufacture and operation, in particular by simplifying the design and reducing the number of parts and components [1].

Improvement of the effectiveness of aircraft engines and similar power units is becoming impossible without application of fundamentally new structural materials. Such materials include alloys based on γ-TiAl intermetallic phases. Owing to a unique set of physical and mechanical properties [2, 3] (high strength and modulus of elasticity, low density, high-temperature strength and high-temperature resistance, high anticorrosion properties, good fatigue fracture and creep resistance), they have for many years preserved their positions in the category of attractive materials for aerospace, transportation industries and in power engineering.

Wide introduction of titanium aluminides into industry is prevented by their low room temperature ductility [4], related to low crystallographic symmetry and insufficient number of slip systems; low cleavage strength; weak grain boundaries, as well as low technological properties [2].

Improvement of technological properties of these materials can be ensured not only by micro- and macroalloying [5], but also by alloy microstructure. Reference [6] shows three main types of titanium intermetallic structures: lamellar (platelike), recrystallized and mixed (duplex). Authors of [7] show that finely-dispersed two-phase duplex structure of Ti–Al based alloys has the best ductility, while another, not less important characteristic, namely, alloy viscosity, is lowered. An optimum variant is producing alloys with a completely lamellar two-phase $\gamma + \alpha_2$ structure with a certain quantity of γ and α_2 phases in the alloy [7].

Titanium aluminide based alloys with different structure types, in addition to aircraft industry [5, 8–10], can be used in various industrial sectors, namely gas- and oil-processing, chemical, as well as in nuclear and transportation engineering [11, 12].

Wider acceptance of γ-TiAl based alloys is promoted by current intensive investigations of their weldability and development of effective measures to improve the strength and reliability of welded joints.

In this connection the purpose of this review is analysis of modern developments of joining processes for titanium aluminide based materials using various kinds of welding.

Arc welding. Reference [3] gives the results of investigation of weldability of an alloy with γ-TiAl cast structure (48 at.% Al and 2 at.% Cr and Nb). Welding of titanium aluminides was conducted without preheating with current adjustment in the range of 50–1500 A. As a result, it was established that microstructure of weld metal zone consists of columnar and equiaxed dendritic structures.

Mechanical properties of weld metal turned out to be lower than those of base metal. This is exactly what was established as a result of tensile testing (Figure 1). At the same time, at low current welding cracks were found in the joint, which formed as a result of increase of α_2-phase amount.

Weldability of the above-mentioned alloy was studied in [14]. Before welding all the samples were subjected to hot isostatic pressing, part of them were heat-treated at the temperature of 1300 °C for 20 h. This resulted in formation of a crystalline structure, consisting of γ-phase, $\gamma + \alpha_2$ colony and Laves phases. Cracking was observed in all the welds, both after their isostatic pressing, and without it.

Bharani and Acoff conducted welding of the above titanium aluminide alloy and wrought γ-TiAl alloy (46 at.% Al, 2 at.% Cr, 2 at.% Nb, 0.9 at.% Mo) without preheating. It is established that shortening of crack length in the welded joint can be achieved only due to performance of postweld heat treatment at 615 °C temperature [15].

Electron beam welding. In the opinion of the authors of [16, 17], fusion welding of titanium aluminide can be performed only with preheating up to 250–650 °C. This is related to the fact that in view of the low ductility (right up to 700 °C) titanium aluminides are quite sensitive to stresses, which develop under the conditions of non-uniform heating in welding and, therefore, are prone to appearance of transverse cold cracks in welded joints.

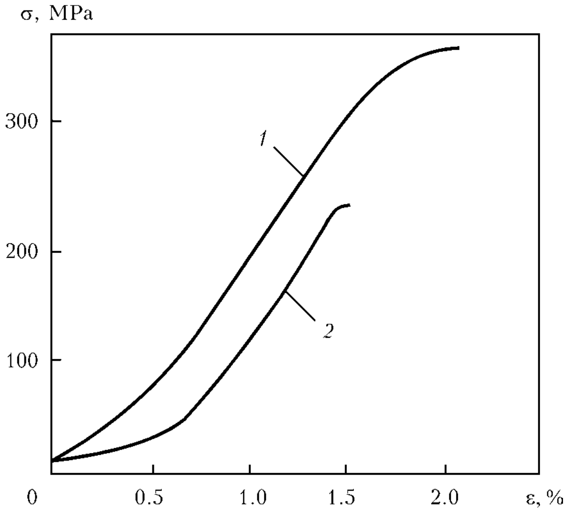

Figure 1. Dependence of deformations σ on stresses ε [13] of base metal (*1*) and weld zone (*2*)

References [16, 17] give preheating temperature without any additional details, and in [18] it is recommended to preheat the samples to be welded up to 400–500 °C to prevent development of transverse cracks in welded joints. On parts of local welds or deposits for repair purposes preheating temperature should be not less than 600 °C. However, these parameters are established only for γ-TiAl alloy (31 at.% Al and 2 at.% Nb and Mn each), while sample preheating is performed in the welding chamber.

Pressure welding in vacuum. During performance of research work authors of [19] used for experimental purposes aluminide samples (20 mm diameter and height titanium) cut out of an ingot subjected to isostatic processing at the temperature of 1260 °C and pressure of 170 MPa for 4 h with subsequent stabilizing annealing at 1000 °C (50 h). Weight fraction of alloying elements and additives in the alloy was equal to, %: 60.95 Ti; 31.15 Al; 4.65 Nb.

Welding was performed at the temperature below $\alpha + \gamma$ transition, so that material structure practically did not change. This enabled eliminating the phenomena, which are due to rapid cooling of the joint. A clear-cut boundary is registered at contact of the joined surfaces. No common grain formation was found. Both single macropores and linear porosity were present in a number of samples.

Further investigations were performed with the purpose of revealing the features of structural transformations in titanium aluminide under the impact of thermodeformational cycle of welding in the following modes: temperature $T = 900$ and 1100 °C, welding time $t = 4$–5 h, pressure $P = 200$–300 MPa [20]. It is established that at welding temperature below 900 °C transcrystalline cracks without any visible traces of plastic deformation develop in the alloy under the impact of a compressive welding force. With increase of welding temperature from 900 up to 1100 °C, structural element morphology changes from coarse-grained platelike to fine-grained globular. At the temperature of 1100 °C, common grains are observed in the joint zone, forming as a result of plastic deformation and subsequent recrystallization of near-contact metal volumes.

Possibility of welding titanium aluminide using a «soft» interlayer was studied later on [19]. The authors assumed that part annealing after welding with an interlayer will lead to its dissolution in the base metal and to diffusion-induced homogenizing of the composition in the joint zone. Therefore, aluminium and titanium as the main alloying elements of the alloy were selected as interlayers. Thickness of aluminium and titanium interlayers was equal to 0.15 and 0.20 mm, respectively. Samples of titanium aluminide (20 mm height and diameter) were used for experiments.

Microstructures of welded joints made with application of aluminium and titanium foil as an interlayer, are given in Figures 2 and 3. It is established that welding of γ-TiAl based alloy with application of aluminium and titanium foil as interlayers does not ensure the required quality of the joints. At application of aluminium interlayer it is possible to produce (after welding and annealing) phase and chemical compositions of metal along the fusion line close to those of base metal. However, these joints are not operable because of the presence of defects which arise in welding (Figure 2). Now in the case of application of titanium foil, welded joints, both after welding and after welding and annealing, feature a certain level of strength at normal temperature. However, it does not seem possible to ensure high-temperature strength of such joints close to that of γ-TiAl, as the joint zone has single-phase structure of α_2(Ti_3Al) (Figure 3).

Friction welding. The main problems at production of operable joints of titanium aluminides in friction welding [21—23] is microcracking in the zone of thermomechanical impact during deformation [21], weld metal cracking during cooling [22], considerable increase of joint zone hardness [21—23], as well as absence of optimum parameters of welding mode [21—23].

Description of structural and phase changes proceeding in the plane of interaction and in the HAZ in two different modes (convection and combined) is given in [24]. It is established that metal structure in the plane of the joint produced at convection welding, differs from that of joint zone metal in the combined mode, in which extremely fine dynamically recrystallized γ-TiAl grains are formed without the presence of the lamellar component, by insufficient quantity of α_2-phase and structural gradient in the radial direction.

It is known that welded joint quality depends on welding time and upset length. References [25, 26] describe investigations on weldability of γ-TiAl and α_2-TiAl alloys using nanointerlayer of Ti/Al foil with different heating times. It is established that in joints produced at heating duration t_h = 1.0 s, an interlayer of up to 100 μm width with a fine-grained structure is observed. With increase of time t_h up to 4.0 s the observed structure in the joint plane and in the HAZ of welded alloys is characterized by presence of extremely fine dynamically recrystallized grains. The authors of the work supposed that formation of fine-grained metal structure in the joint plane

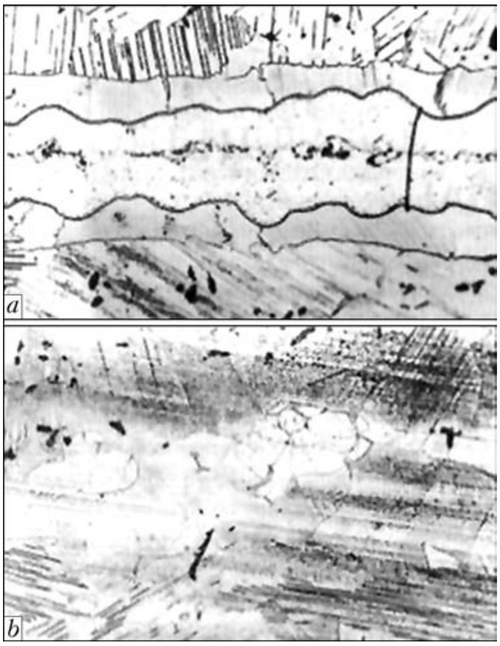

Figure 2. Microstructures of welded joints of γ-TiAl alloy with aluminium interlayer: *a* — after welding (×400); *b* — after welding and annealing (×200) [19]

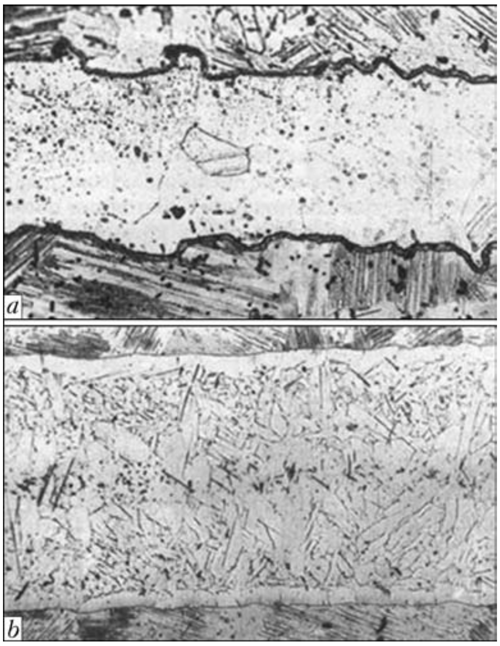

Figure 3. Microstructures of welded joint of γ-TiAl alloy with titanium interlayer: *a* — after welding (×250); *b* — after welding and annealing (×100) [19]

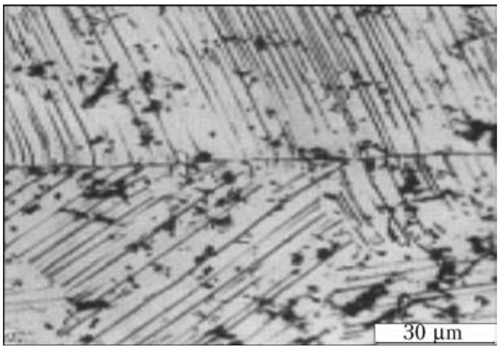

Figure 4. Microstructure of metal of the zone of γ-TiAl alloy welded joint produced by vacuum diffusion welding [28]

promotes an increase of butt metal resistance to cracking during cooling.

Diffusion welding. Reference [27] deals with γ-TiAl alloy (49 % Ti, 47 % Al and 4 % Cr, Mn, Nb, Si, B each) produced by the process of precision casting and hot pressing with subsequent homogenizing annealing. As shown by investigation results, formation of a lamellar structure in the vicinity of the weld is provided in the following welding mode: T = 1000–1100 °C, t = = 3 h, P = 20–40 MPa with subsequent heat treatment.

Reference [28] presents the results of investigations, conducted on Ti — 48 at.% Al alloy alloyed with niobium and manganese. Titanium aluminide joints were produced by diffusion welding in vacuum without the interlayer at T = = 1200 °C and P = 70 MPa with subsequent soaking for 20 min. Figure 4 shows the microstructure of joint zone metal.

The authors of the work found that the interface is an interlayer of intermetallic, the composition of which, by the data of local chemical analysis, is close to that of Ti_3Al intermetallic. Presence of a brittle intermetallic interlayer lowers welded joint strength, thus leading to lowering of its service characteristics.

In order to improve the welding processes and properties of permanent joints of γ-TiAl alloys, the authors of [29–32] applied nanostructured interlayers, which were placed between the item surfaces to be welded. Such interlayers can be one- or multilayer coatings [29–31] or foils [32].

In [29-31] weldability of γ-TiAl alloy was studied at application of various nanolayered coatings, which were applied on the surfaces being welded by magnetron sputtering. Reference [31] shows application of coatings of titanium, vanadium, chromium and manganese 0.5–1.5 μm thick, and [29–30] describe application of coatings of Ti/Al system of Ti — 48–50 at.% Al composition, the thickness of which was equal to 2.0–2.5 μm at individual layer thickness of up to 4 nm.

It was established [31] that application of vanadium, chromium and manganese coatings improves ductility of welded joints of γ-TiAl alloys, at atomic fraction of the above elements in the welded joints on the level of 1–3 %.

In [29, 30] it is shown that deposition of thin nanolayered Ti/Al coatings on the surfaces being joined provides formation of a uniform microstructure in the joint zone during diffusion welding at the temperature of 1000 °C. The authors came to the conclusion that formation of a strong welded joint in the temperature range of 700–1100 °C is related to dynamic recrystallization of γ-TiAl alloy which leads to structure refinement and ensures running of plastic deformation.

Investigation of weldability of γ-TiAl based alloy with application of nanolayers produced by the technology described in [33], was performed by the authors of [32]. Welding was conducted on 10 × 10 × 6 mm samples from γ-TiAl intermetallic (48 at.% Al, 2 at.% Nb, 2 at.% Mn), for which the following interlayers were chosen: Ti/Al (Ti — 38 at.% Al), Ni/Ti (Ti — 44 at.% Ni) and Ni/Al (Al — 46 at.% Ni) (Figure 5).

The authors established that during diffusion welding of γ-TiAl samples with application of Ni/Ti and Ni/Al nanolayers, a transition zone of heterogeneous structure and composition

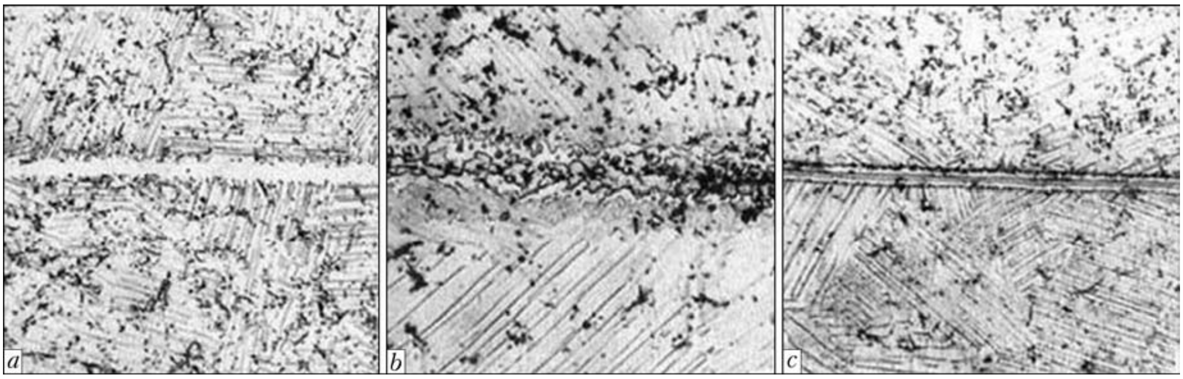

Figure 5. Microstructures of γ-TiAl alloy joint zone at diffusion welding with application of nanolayers [32]: *a* — Ti/Al (×200); *b* — Ni/Ti (×200); *c* — Ni/Al (×400)

forms in the joint zone [32]. At application of Ti/Al nanolayers an intermetallic forms in the joint zone, the composition of which corresponds to the initial γ-TiAl intermetallics, layer-by-layer transforming into γ-TiAl with nanometric periods (less than 200 nm). Such changes of metal composition and structure in the joint zone are indicative of a high diffusion mobility of components that may be due to the processes of heat generation accompanying solid-phase reactions, initiated in nanolayered foil at heating [34].

Resistance welding. Reference [35] gives the results of investigations of the features of formation of γ-TiAl based welded joints by resistance welding technology. Such a technology provides local high-rate application of heat to the joint zone [36] that prevents metal softening. Considering the experience of previous developments on flash-butt welding of difficult-to-weld materials [37], welding of γ-TiAl alloys was conducted with application of nanostructured foils of Ti/Al system. At application of foil consisting of titanium and aluminium layers, additional heat evolution in the contact zone takes place that is due to running of an exothermal reaction between metals, that results in welding time shortening by 0.5–0.7 s on average. It is additionally shown in the work that nanolayered foils should be applied in order to ensure uniform heating, improve welded joint formation and properties. Foil thickness can vary from 60 up to 100 μm.

Conclusions

1. Applications of traditional welding processes, based on local melting of material in the joint zone showed that the quality of the produced welded joint essentially depends on phase transformations in the HAZ zone. At deviation of welding mode from the optimum one in the joint zone phase transformations take place, which are accompanied by volumetric effects leading to development of stresses in the HAZ zone and, as a result, cracks form in its vicinity.

2. The highest values of mechanical properties of titanium aluminide joints were produced in diffusion welding with application of thin interlayers. This welding process, however, was not accepted by industry. One of the main disadvantages of diffusion welding is the need for long-term heating up to high temperatures (T = 1000–1100 °C) of the entire item to be welded and presence of vacuum.

3. Application of composite interlayers in resistance welding provides a more uniform and concentrated heating, and, as a result, sound joints of parts of a small cross-section (100–200 mm^2) from titanium aluminides that is indicative of applicability of such technologies at industrial-scale manufacture of various components.

4. Results presented in the published works, are indicative of high efficiency of application of nanostructured interlayers for joining difficult-to-weld γ-TiAl alloys.

1. Mukhin, V.S. (2007) *Principles of technology of machine building (aircraft engine engineering)*. Ufa: UGATU.
2. Pavlinich, S.P., Zajtsev, M.V. (2011) Application of intermetallic titanium alloys in casting of assemblies of gas turbine engines and blades with lightened high strength structures for aircraft engines of new generations. *Vest. Ufim. Gos. Aviats. Tekhn. Un-ta*, 15(**4**), 200–202.
3. Ivanov, V.I., Yasinsky, K.K. (1996) Efficiency of application of heat resistant alloys based on Ti_3Al and TiAl intermetallides for service at 600–800 °C temperatures in aircraft engineering. *Tekhnol. Lyogk. Splavov*, **3**, 7–12, 93.
4. Lipsitt, H.A., Shechtman, D., Schafrik, R.E. (1975) The plastic deformation of TiAl. *Met. Transact. A*, **6**, 1991–1998.
5. Froes, F.H., Suryanarayana, C., Eliezer, D. (1991) Production, characteristics and commercialization of titanium aluminides. *ISIJ Int.*, 31(**10**), 1235–1248.
6. Polkin, I.S., Kolachev, B.A., Iliin, A.A. (1997) Titanium aluminides and alloys on their base. *Tekhnol. Lyogk. Splavov*, **3**, 32–39.
7. Kazantseva, N.V., Grinberg, B.A., Gulyaeva, N.P. et al. (2003) Microstructure and plastic deformation of orthorhombic Ti_2AlNb alloys II. Structure and phase transformations in strong deformation. *Fiz. Metalla i Metallovedenie*, 96(**4**), 23–32.
8. Kim, Y.-W., Dimiduk, D.M. (1991) Progress in the understanding of gamma titanium aluminides. *JOM*, **8**, 40–47.
9. Bannykh, O.A., Povarova, K.B., Braslavskaya, G.S. et al. (1996) Mechanical properties of cast alloys γ-TiAl. *Metallovedenie i Term. Obrabotka Met.*, **4**, 11–14.
10. Boggs Robert, N. (1989) Titanium aluminide true space-age material. *Des. News*, 45(**12**), 51–53.
11. Antashaev, V.G., Ivanov, V.I., Yasinsky, K.K. (1996) Development of technology for producing of cast parts from intermetallic alloy TiAl and their application in structures. *Tekhn. Lyogk. Splavov*, **3**, 20–23.
12. Hino, H., Nisiyamo, Yu. (1990) Application of titanium aluminides. *Metals Technol.*, 60(**7**), 70–76.
13. Arenas, M.F., Acoff, V.L. (2003) Analysis of gamma titanium aluminide welds produced by gas tungsten arc welding. *Welding J.*, **5**, 110–115.
14. Kelly, T. (1992) Repair welding of gamma titanium aluminide castings. In: *Proc. of the 3rd Int. SAMPE Metals Conf.* (Covina, 25–30 May 1992). Covina: SAMPE, 1992.
15. Bharani, D.J., Acoff, V.L. (1998) Autogenous gas tungsten arc weldability of cast alloy Ti–48Al–2Cr–2Nb (atomic percent) versus extruded alloy Ti–46Al–2Cr–2Nb–0.9Mo (atomic percent). *Met. and Mater. Transact. A*, 29(**13**), 927–935.
16. Patterson, R.A. et al. (1990) Titanium aluminide : electron beam weldability. *Welding J.*, **1**, 39–44.
17. Jensen, C.M., Zhang, H., Baeslack, W.A. et al. (1998) The effect of postweld heat treatment on the structure and properties of electron beam welded Ti–48Al–2Cr–2Nb alloy. In: *Abstr. of Papers of 79th AWS Annual Meeting* (Miami, AWS).
18. Kharchenko, G.K., Ustinov, A.I., Falchenko, Yu.V. et al. (2001) Choice of preheating temperature of γ-

aluminide titanium in EBW. *The Paton Welding J.*, **11**, 20–23.

19. Yushtin, A.N., Zamkov, V.N., Sabokar, V.K. et al. (2001) et al. (2001) Pressure welding of intermetallic alloy γ-TiAl. *Ibid.*, **1**, 33–37.
20. Zamkov, V.N., Markashova, L.I., Kireev, L.S. (1992) Peculiarities of structural changes of heat resistant alloy based on Ti_3Al in vacuum pressure welding. *Avtomatich. Svarka*, **9/10**, 13–16.
21. Baeslack, W., Threadgill, P., Nicholas, E. (1992) Linear friction welding of alpha-two titanium aluminide. *TWI Research Report*, **442**, 204–210.
22. Miyashita, T., Hino, H. (1994) Friction welding characteristics of TiAl intermetallic compound. *J. Japan Inst. Metals*, 58(**2**), 215–220.
23. Baeslack, W., Threadgill, P., Nicholas, E. et al. (1995) Linear friction welding of Ti–48Al–2Cr–2Nb (at.%) titanium aluminide. In: *Proc. of the 8th World Conf. on Titanium* (Birmingham, 22–26 Oct. 1995). Birmingham: Inst. of Materials, 1995.
24. Kuchuk-Yatsenko, S.I., Zyakhor, I.V. (2009) Specifics of friction welding of titanium aluminides. In: *Proc. of 9th Math. Annual Int. Conf. on Efficiency of Implementation of Scientific, Resource and Industrial Potential in Current Conditions* (Slavskoe, 9–13 February 2009). Kiev: UIC Science. Technique. Technology, 2009.
25. Zyakhor, I.V., Kuchuk-Yatsenko, S.I., Ustinov, A.I. (2009) Application of nanolayered foil of Ti–Al system in friction welding of titanium aluminide based alloys. In: *Proc. of Conf. on Slavic Lectures* (Lipetsk, 4–5 June 2009). Lipetsk: LGTU, 2009.
26. Zyakhor, I.V., Kuchuk-Yatsenko, S.I. (2009) Structure of titanium aluminide compounds in friction welding using nanolayered foil of Ti–Al system. In: *Proc. of 8th All-Russ. Sci.-Techn. Conf. with Internat. Participation* (Moscow, 30 November-1 December, 2009). Moscow: MATI, 2009.
27. Cam, G., Bohm, K.-H., Kocak, M. (1999) Diffusionsschweissen feingegossener Titanaluminide. *Schweissen und Schneiden*, **8**, 470–475.
28. Ustinov, A.I., Falchenko, Yu.V., Ishchenko, A.Ya. et al. (2009) Producing permanent joints of γ-TiAl based alloys using nanolayered Ti/Al interlayer by vacuum diffusion welding. *The Paton Welding J.*, **1**, 12–15.
29. Duarte, L.I., Ramos, A.S., Viera, M.F. et al. (2006) Solid-state diffusion bonding of gamma-TiAl alloys using Ti/Al thin films as interlayers. *Intermetallics*, **14**, 1151–1156.
30. Ramos, A.S., Viera, M.T., Duarte, L.I. et al. (2006) Nanometric multilayers : A new approach for joining TiAl. *Ibid.*, **14**, 1157–1162.
31. Yan, R., Somekh, R.E., Wallach, E.R. (1992) Solid-state bonding of TiAl with interlayers. In: *Proc. of the 3rd Int. Conf. on Trends in Welding Research* (Gattinburg, Tennessee, USA, 1–5 June, 1992). Ohio: ASM International, Materials Park, 1992.
32. Kharchenko, G.K., Ustinov, A.I., Falchenko, Yu.V. et al. (2011) Diffusion bonding of γ-TiAl base alloy in vacuum by using nanolayered interlayers. *The Paton Welding J.*, **3**, 2–6.
33. Ustinov, A.I., Olikhovskaya, L.A., Melnichenko, T.V. et al. (2008) Solid phase reactions in heating of multilayer Al/Ti foils produced by electron beam deposition method. *Advances in Electrometallurgy*, **2**, 19–26.
34. Kuchuk-Yatsenko, S.I., Shvets, V.I., Sakhatsky, A.G. et al. (2009) Features of resistance welding of titanium aluminides using nanolayered aluminium-titanium foils. *Ibid.*, **3**, 11–14.
35. Kochergin, A.K. (1987) *Resistance welding*. Leningrad: Mashinostroenie.
36. Kuchuk-Yatsenko, V.S., Shvets, V.I., Sakhatsky, A.G. et al. (2007) Specifics of resistance butt welding of aluminium alloys by using nanostructural aluminium-nickel and aluminium-copper foils. *Svarochn. Proizvodstvo*, **9**, 12–14.

Received 01.03.2013