PRODUCING PERMANENT JOINTS OF γ-TiAl BASED ALLOYS USING NANOLAYERED Ti/Al INTERLAYER BY VACUUM DIFFUSION WELDING

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The possibility of producing diffusion bonds of γ-TiAl based alloys using nanolayered Ti/Al interlayer has been studied. It is shown that utilization of nanolayered foil as an intermediate element allows formation of sound joints in vacuum diffusion welding. Peculiarities of microstructure of the joint zone have been studied.

Keywords: *vacuum diffusion welding, titanium aluminide, structure, joint zone, nanolayered interlayer*

γ-TiAl based alloys are regarded as promising materials for manufacture of structural elements of aerospace system components operating at higher temperatures. The advantages of such alloys, compared to other high-temperature materials, mainly are their low (3.8--4.0 g/cm^3) density and high heat resistance [1].

The prospects of using γ-TiAl alloys in structural element design stimulated investigation and developments in the field of the technology of producing permanent joints of these alloys. A possibility of producing permanent joints by fusion [2] and diffusion [3--7] welding was considered.

Application of the traditional welding processes based on local melting of material in the joint zone showed that the quality of the produced welded joint depends essentially on phase transformations in the HAZ. At deviation of the welding mode from the optimum one, phase transformations accompanied by bulk effects occur in the joint zone, this leading to development of stresses in the HAZ and, as a result, to crack initiation near it [2]. In order to avoid it, welding has to be performed in strictly specified modes.

Use of vacuum diffusion welding is believed to be promising. Possible technological variants of this welding process for welding titanium aluminides are considered in [3--7]. Study [3] gives the results of vacuum diffusion welding of γ-TiAl alloy (49 % Ti, 47 % Al and 4 % Cr, Mn, Nb, Si, B) produced by the method of precision casting and hot pressing with subsequent homogenizing annealing in the following mode: welding temperature T = 950--1100 °C, welding time τ = 1--3 h, pressure P = 20--40 MPa, heat treatment at 1400 °C, 30 min. The authors determined the optimum welding mode: T = 1000--1100 °C, τ = 3 h, P = 20--40 MPa. Heat treatment ensures formation of the lamellar structure in the weld area. In [4] the possibility of pressure welding of Ti--Al--Nb alloy based on α_2-Ti$_3$Al (T = 900, 1000 and 1100 °C, τ = = 4--5 min, P = 200--300 MPa) was studied. Joints produced at T = 1000--1100 °C have equivalent strength with the base metal (σ_t = 800--820 MPa).

It is known that additional activation of the welded surfaces can be achieved when using interlayers, which are ductile or consist of two foils based on different elements, in which contact melting processes develop at temperature increase. So, [5] is a study of the possibility of using aluminium and titanium interlayers 0.15 and 0.20 mm thick, respectively, in pressure welding of γ-TiAl alloy (60.947 % Ti, 31.152 % Al, 4.65 % Nb, 2.73 % Mn. 0.31 % B). Welding was performed in the following mode: T = 750--850 °C, τ = = 10--20 min, P = 100 and 300 MPa with subsequent stabilizing annealing at 1000 °C, 50 h. The authors note that use of aluminium interlayers leads to formation of defects in the joint zone, namely microvoids and cracks. When titanium interlayers are used, a joint zone forms, which features a high strength, and considerable chemical and phase inhomogeneity.

In [6, 7] it is shown that deposition of thin nanolayered Ti/Al coatings on the surfaces of γ-TiAl alloy samples to be joined ensures a uniform structure in the joint zone in vacuum diffusion welding (T = = 1100 °C). The authors came to the conclusion that formation of a strong welded joint at 700--1100 °C is related to dynamic recrystallization of γ-TiAl alloy, thus promoting refinement of its structure and initiation of plastic deformation.

On the other hand, the process of deposition of such coatings on the part surfaces to be joined runs into certain technological difficulties in a number of cases. The technology of producing permanent joints is simplified when nanolayered materials in the form of foil are used. Such an approach was implemented by us, for instance, in welding of composite materials based on Al--Al$_2$O$_3$ using nanolayered Ni/Al foil [8]. The method of electron beam deposition enables producing nanolayered foil over a short enough period, owing to a high (up to 100 nm/s) rate of the deposition process. Conditions of formation of permanent joints using nanolayered Ti/Al foils as an interlayer were studied.

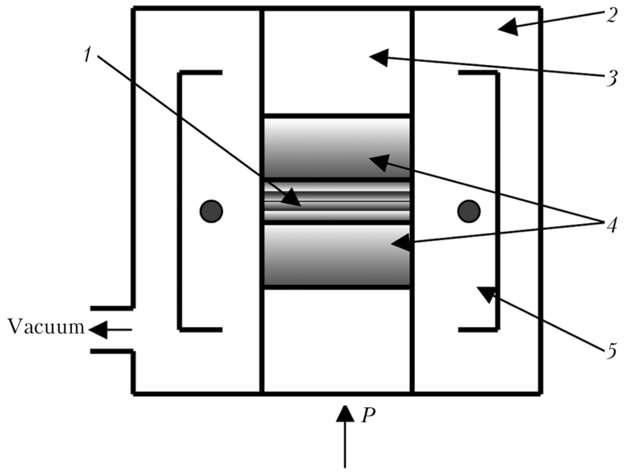

Figure 1. Schematic of the unit for vacuum diffusion welding: *1* — nanolayered interlayer; *2* — vacuum chamber; *3* — press-down rod; *4* — welded samples; *5* — electron beam gun

Nanolayered Ti/Al foil was produced by layer-by-layer electron beam deposition of elements on a horizontal rotating substrate by a procedure described in several studies (see for instance [9]). Schematic of the process of foil formation is given in [10]. To perform layer-by-layer deposition of elements, the vacuum chamber was separated by a vertically located continuous screen into two equal parts, in each of which copper water-cooled crucibles were installed, one of them accommodating an ingot of titanium, and the other — an ingot of aluminium. The substrate was fastened on a vertical shaft located above the separating screen. Electron beam gun performed heating of the substrate up to the specified temperature, which was monitored during deposition by a thermocouple. Before deposition, a layer of CaF_2 was applied on the substrate, which promoted interlayer separation from the substrate. Then electron beam guns were used to induce a molten pool on the ingot surfaces, from which the elements were evaporated. Substrate rotation and presence of a separating screen allowed successive deposition of metal layers. The ratio of thickness of these layers was determined by the ratio of the ingot evaporation intensity, and their total thickness varied, depending on the substrate rotation speed. Total thickness of the interlayer at the set intensity of element evaporation depended on the duration of the deposition process.

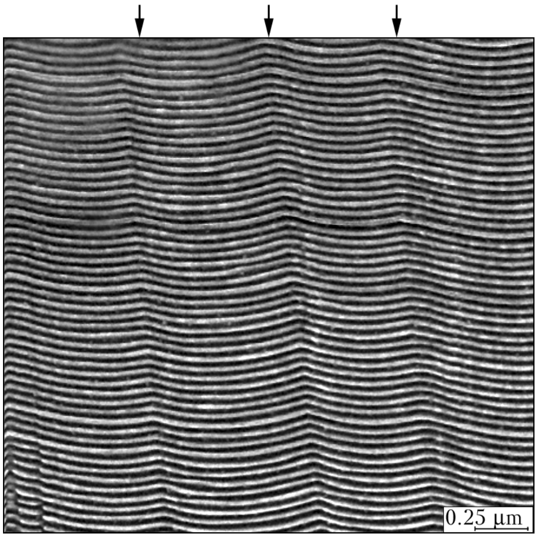

Figure 3. Cross-sectional microstructure of nanolayered foil in the initial condition: light layers correspond to titanium, dark ones — to aluminium; arrows show grain boundaries

Ti–48 at.% Al alloy with niobium and manganese additives was selected as the object of study. This alloy belongs to the group of titanium intermetallics, which are in the two-phase state ($\alpha_2 + \gamma$) with α_2-Ti_3Al and γ-TiAl (furtheron TiAl).

Welding was performed in a vacuum chamber fitted with a system of static loading of samples and their heating (Figure 1). Electron beam gun was used as the heat source. Welding process parameters were varied within the following ranges: T = 900–1200 °C, τ = 5–25 min, P = 10–70 МПа. Pressure in the working chamber was maintained on the level of $1.33.10^{-3}$ MPa.

Before welding sample surfaces were ground on a diamond wheel, and then degreased. Prepared samples of 10 × 10 × 4 mm size together with the interlayer were placed into the vacuum chamber. Uniform heating was ensured by a ring-shaped electron beam gun, installed on the butt level, and heating correction during welding was performed by heater displacement along the assembly of the samples being welded. Welding temperature was monitored by a thermocouple.

In order to conduct metallographic analysis welded joint samples were prepared by a standard procedure

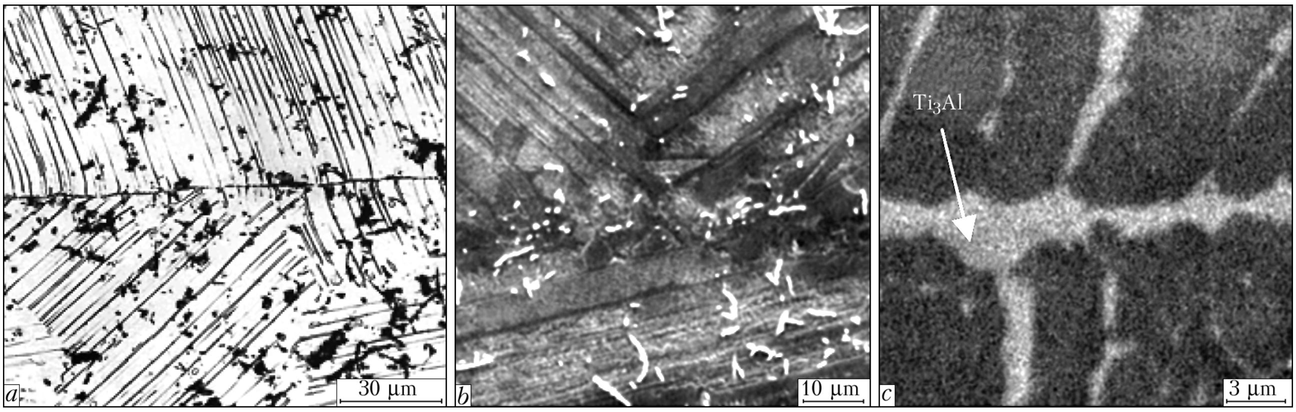

Figure 2. Microstructure of the zone of TiAl joint produced by vacuum diffusion welding without an interlayer: *a*–*c* — see the text

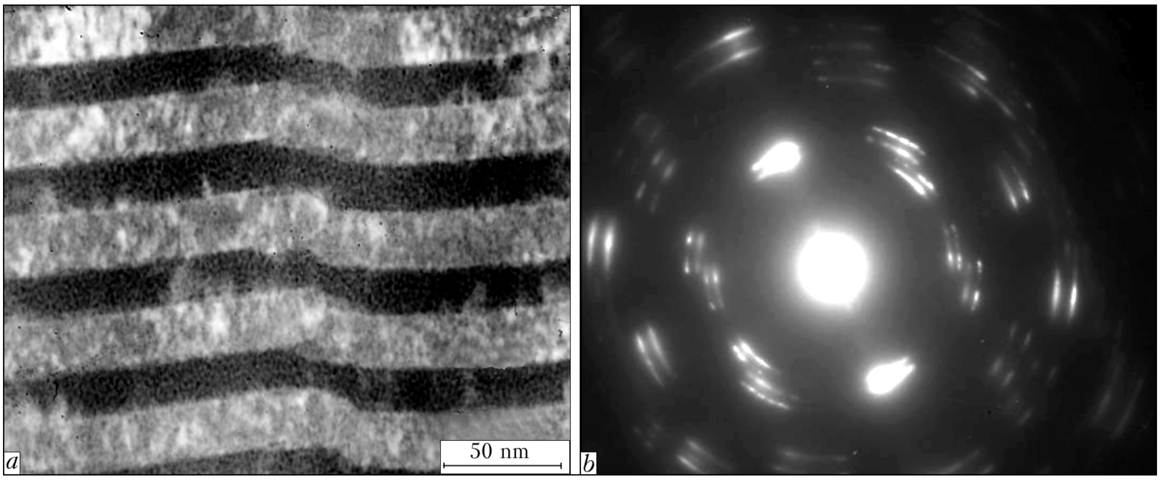

Figure 4. Microstructure (*a*) and microdiffraction pattern (*b*) of the nanolayered interlayer cross-section

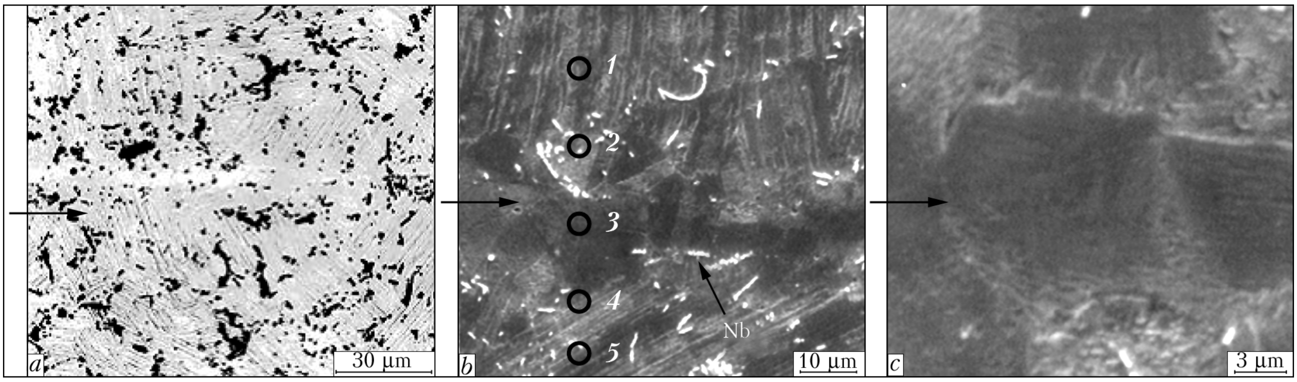

Figure 5. Microstructure of the zone of the joint of TiAl intermetallic samples produced by diffusion welding in vacuum using nanolayered Ti/Al foil: *a*–*c* — see the text; the arrows show the welding location; numbers are points in which the local composition and microhardness were studied; results of these measurements are given in the Table

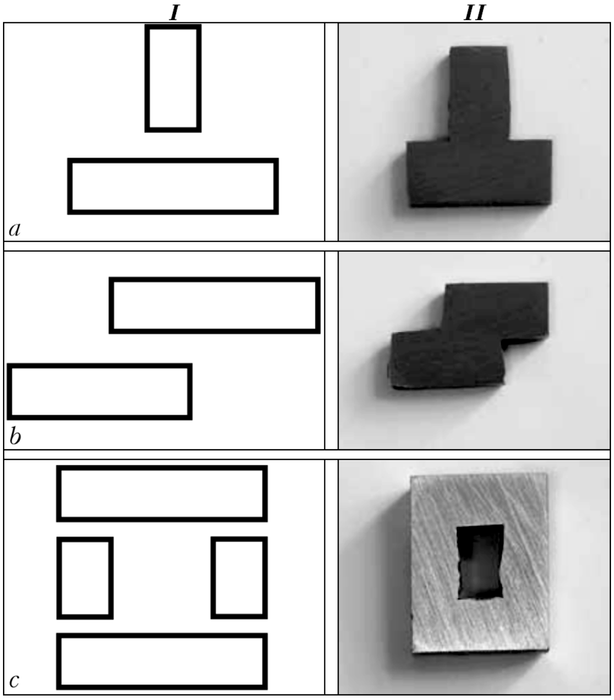

Figure 6. Schematic of sample assembly (*I*) and general view (*II*) of TiAl alloy welded joints of tee (*a*), overlap (*b*) and box-like (*c*) type made using nanolayered Ti/Al interlayer

in the Struers grinding-polishing machine tool Abramin. The condensate structure and chemical composition were analyzed using Neophot optical microscope and CamScan scanning microscope, fitted with an energy-dispersion system Energy 200 for local analysis. Chemical etching of the samples was conducted to reveal the weld metal structure. Condensate microhardness was measured by a micorhardness attachment to Polyvar-Met optical microscope at the load of 0.098--0.196 N by Vickers. The structure of nanolayered foil on transverse sections was analyzed using Hitachi transmission electron microscope H-800 at 200 kV accelerating voltage. The thin foil cross-section was first prepared by mechanical thinning, and then polished in Gatan 656 unit with subsequent thinning and bombardment of the surface at 3° angle by argon ions with 5 keV energy at ion gun current of 20 µA in PIPS 691 unit.

TiAl joints were produced by vacuum diffusion welding without an interlayer at T = 1200 °C and P = 70 MPa with subsequent soaking for 20 min. Joint zone microstructure is shown in Figure 2. It is seen in the Figure that an interface is revealed in the above zone (Figure 2, *a*) without any pores in the joint (Figure 2, *b*). Structure analysis in phase contrast mode revealed that the interface is an intermetallic interlayer, 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 the welded joint strength, thus leading to a degradation of its surface properties.

Nanolayered Ti–52 at.% Al foil 20 μm thick with 50 nm period of layer alternation (titanium and aluminium) was used in this study for diffusion welding of TiAl intermetallic samples. Its cross-sectional microstructure (Figure 3) shows that it is divided into individual grains. Within one grain a striated contrast is observed, which corresponds to alternation of titanium and aluminium layers. Transmission electron microscopy investigations were conducted to determine the characteristics of the laminated grain structure. Figure 4 gives the microstructure and microdiffraction pattern of the cross-section of nanolayered Ti/Al foil. Absence of element mixing is indicated by microdiffraction of electrons on the studied section (Figure 4, *b*). Certain orientational relationships characteristic for laminated materials are found between the layers. From the light-field images it can be seen (Figure 4, *a*) that the period of alternation of titanium and aluminium layers is equal to 50 nm.

The regularities of the diffusion processes running in nanolayered foil at its heating are analyzed in [9]. It is established that heating promotes their intensive development, this leading to formation of a heterophase structure consisting of a mixture of TiAl and Ti_3Al intermetallics. On this basis it was assumed that during diffusion welding of titanium intermetallics phase transformations will run in the foil, which will ensure formation of a structure similar to that of the base metal, in the joint zone.

Investigations of the influence of diffusion welding parameters (pressure, heating temperature and soaking time) on welded joint quality were conducted to determine the conditions of joint formation using nanolayered foils. It is found that at lowering of welding temperature (below 1000 °C) the joint zone develops discontinuities, which considerably lower its mechanical strength. Microstructure of the zone of a welded joint made in the optimum welding mode ($T = 1200$ °C, $\tau = 20$ min, $P = 10$ MPa) is given in Figure 5. In Figure 5, *a* it is seen that a poorly distinguishable interlayer is present in the joint zone, the composition of which (49.4 Al; 49.8 Ti; 0.8 Mn) is close to that of the initial intermetallic, by the data of local chemical analysis.

The interlayer has a uniform structure (Figure 5, *b*) and consists of equiaxed grains of up to 10 μm size (Figure 5, *c*), in which a lamellar structure is discernible, which is characteristic of the initial intermetallic. Absence of pores and cracks, both in the joint zone and on the boundary with the welded samples, is indicative of a high quality of the produced welded joint. It should be noted that no degradation of the welded intermetallic structure occurs in the above welding mode. Element distribution in the joint zone and microhardness of different sections of the welding zone are given in the Table. From Figure 5, *b* and the Table it is seen that manganese is present and niobium is absent in point *3*. According to metallographic and local chemical analysis, niobium particles accumulate on the interlayer--intermetallic interface. Manganese presence in the interlayer is indicative of running of the diffusion processes in the joint zone during development of the solid-phase synthesis reaction, initiated in the nanolayered interlayer during welding.

Composition (at.%) and *HV* microhardness of different sections of the welded joint zone

Studied points of the joint zone (see Figure 5, *b*)	Al	Ti	Mn	Nb	*HV*, GPa
1	43.9	52.9	1.3	1.9	4.6
2	47.3	50.1	0.9	1.7	4.8
3	49.4	49.8	0.8	--	4.0
4	47.4	49.9	1.0	1.7	4.3
5	44.1	52.6	1.5	1.8	4.4

Intensive development of the diffusion processes in the joint zone as a result of application of nanolayered interlayers promotes producing sound welded joints. As an example Figure 6 gives the general view of samples of welded joints of tee, overlap and box-like types.

Thus, during diffusion welding of intermetallic samples using nanolayered Ti/Al interlayer, the joint zone develops an intermetallic, the composition of which corresponds to the initial TiAl intermetallic (see the Table). Such changes of the metal composition and structure in the joint zone are indicative of the high diffusion mobility of the components, and can be due to the heat evolution processes accompanying the solid-phase reactions initiated in the nanolayered foil by heating [9].

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